NATURALWATER STORAGE AND CLIMATE CHANGE RESILIENCY IN MONTANA: A GEOSPATIAL APPROACH

by

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DEDICATION

For my family, friends, and classmates who have always encouraged me; and for their unwavering love and support.

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GLOSSARY OF ABBREVIATIONS

CRFWS	California Roundtable on Food and Water Supply
DEM	Digital Elevation Model
DEQ	Department of Environmental Quality
DNRC	Department of Natural Resources and Conservation
DOR	Department of Revenue
FLU	Final Land Unit
GIS	Geographic Information Science
GWAAMON	Ground Water Assessment and Monitoring Program
GWAP	Ground Water Assessment Program
LiDAR	Light Detection and Ranging
MBMG	Montana Bureau of Mines and Geology
MSDI	Montana Spatial Data Infrastructure
MSR	Musselshell River
MSRB	Musselshell River Basin
MSWP	Montana State Water Plan
MWC	Musselshell Watershed Coalition
NAIP	National Agricultural Imagery Program
NLCD	National Land Cover Database
NRCS	Natural Resources Conservation Service
NWI	National Wetlands Inventory
PRMS	Precipitation-Runoff Modeling System
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
TIN	Triangulated Irregular Network
USGS	United States Geological Survey

ABSTRACT

Climate change is projected to affect the quantity, quality, and timing of water availability in Montana, including a shift toward earlier spring runoff and more winter precipitation as rain. Montana state agencies have expressed the need to mitigate drought and damage from extreme flood events by identifying new locations for more efficient water storage. In the 2015 Montana State Water Plan, the Department of Natural Resources and Conservation (DNRC) identifies natural storage infrastructures (floodplains, wetlands, riparian areas) as valuable tools to increase drought resiliency and mitigate water shortage. Quantifying how much water can be stored through natural storage has been a key question for Montana water planners. This study addresses western state management needs for a cost- and time-effective method of estimating floodplain water storage potential and provides a GIS-based model that identifies potential natural storage sites using open-source data. The result is a range of storage capacities for a study site near Melstone, Montana, under eight natural water storage conditions. Storage potentials ranged from 934 m^3 for small flood extents to 321,252 m^3 for large floods. This model can be refined using additional hydraulic inputs, and re-scaled to address more complex questions probing the efficacy of natural infrastructure-based water storage in the western United States.

CHAPTER 1

INTRODUCTION

Water Resources and Climate Change in Montana

There is a global consensus among leading climatologists that human activity is leading to a less predictable and generally warmer climate [1]. Research in western North American climatology has found evidence of and projects further shifts in the timing of stream runoff and peak streamflow linked to increasing winter rain and declining snowpack resulting from anthropogenic climate warming [2,3]. Though a changing climate has far-reaching implications for global freshwater supplies, the human impact on water is also evident at local scales. In Montana, there is growing concern about water supplies in the face of increasing water demands and climate change. To address these concerns, there have been statewide management efforts to collect more data on water resources through increased investment in stream gage systems, the groundwater atlas, and an ambitious 2015 State Water Plan. There is a particular concern for water shortage and flood mitigation among water managers within various institutions. In 2015, Governor Steve Bullock released a report on the potential for drought and flooding in Montana which indicated that the potential for impacts from drought in the state is moderate to high [4]. The Governor's report indicated that Montana experienced its highest monthly August precipitation on record in 2014, but well-above average March temperatures and below-average snowfall led to declines in surface water supply in all Montana basins by April 2015.

Drought in Montana has been a mounting concern. In July 2015, 15 of the state's 56 counties were designated as primary natural disaster areas due to drought by the United States Department of Agriculture, with nine additional counties named as contiguous disaster counties [5]. By October 2015, the Montana Department of Natural Resources and Conservation (DNRC) reported that 22 counties had moderate to extremely dry moisture conditions, with none of the state's counties showing above average water supply [6]. Though most basins experienced above normal precipitation during December 2015, by the beginning of 2016 nearly half of Montana's 54 basins had slightly to extremely dry surface water conditions, with only the Kootenai Basin below Libby Dam showing "near average" surface water conditions [7,8]. As of February 2016, the United States Drought Monitor estimated that 433,000 Montanans were living in drought areas [9].

Water Management and Planning in Montana

Montana's quality of life and economy depend on water. Water planning and management are complicated by state efforts to review and enforce historic water rights, rapid urbanization and population growth, and the widespread conversion to more efficient agricultural irrigation methods on Montana farms and ranches. Even as a headwater state, balancing competing water demands with uncertain future water supplies is an important component of water management [10].

The DNRC was formed in 1971 to help ensure Montana's water resources provide benefits for present and future generations. Its Water Adjudication Bureau assists in the process of reviewing all water rights claims made before the 1972 redrafting of

Montana's state constitution [11,12]. In Montana, water rights adjudication is the process of examining and resolving existing water rights claims and issues, as well as the issuance of decrees indicating the completion of a water right review. Through the enforcement of water rights, Montana's adjudication process helps protect water users, and the number of requests calling for water right enforcement on streams has been increasing [13]. As of January 2016, the Water Adjudication Bureau has been responsible for the reexamination of 98,000 water right claims throughout the state, with the most significant enforcement action occurring along the Musselshell River (MSR) [14].

The need for adjudication in Montana has intensified with a rapidly growing population. Some of the state's largest basins and groundwater aquifers have been closed to new appropriations of water due to issues related to resource availability, contamination, and concern for protecting existing water rights [15]. Basin closures were intended to mitigate potential shortage by requiring new diversions of water to be secured through the purchase of an existing water right, or by filing a permit for new wells pumping in excess of 59,600 cubic meters (m^3) per year [16,17]. However, the existence of some administrative loopholes enabled the extensive drilling of new wells that were exempt from the requirement of DNRC review. For example, the predominant purpose of allowing some wells to be exempt from the permitting process was to provide water for the small (e.g. domestic) needs of rural Montanans removed from a municipal water supply without significantly impacting the larger groundwater source [18,19]. The unexpected profusion of permit-exempt wells – drilled mainly in western Montana over the last 20 years – had the unintended consequence of lowering groundwater tables in

municipal aquifers [20]. This proliferation was due largely to housing developers who seized the exempt well loophole to cut development costs by purchasing agricultural land and building subdivisions beyond community boundaries where connection to municipal supplies is more expensive, thus contributing to dramatic and unwelcome urban sprawl [21,22].

Along with rapid population growth, statewide concerns for future water availability are also highlighting the widespread conversion to more efficient methods of agricultural irrigation. The pervasiveness of agriculture in Montana has prompted the intensive diversion of surface and groundwater for agricultural irrigation, which in Montana accounts for 96% of all surface and groundwater withdrawn for any purpose [23–25]. Recent advancements in irrigation technology have altered the way farmers and ranchers grow crops and the rate at which those crops consume water. The conversion to more efficient irrigation methods continues to improve the economic livelihoods of farmers throughout the West by increasing the efficiency of water use per crop unit, leading to higher yields. However, the increased crop yields afforded by highly efficient irrigation systems also lead to the irrigation of more land altogether, thereby increasing the net consumption of water [26–28].

For instance, two common methods of irrigation in Montana – flood and center pivot – vary dramatically in their water use efficiencies, with center pivot irrigation being significantly more efficient than flooding. Despite its efficiency, the conversion from flood to sprinkler irrigation systems has actually tended to increase the consumption of water by extending the ability to divert water during low flow periods and generally

leaving less water available for diversion by downstream water users [24,29]. This phenomenon results in part from the irrigator's newfound ability provided by a center pivot or wheel-lined sprinklers to irrigate previously inactive farmland that was not able to be flood irrigated due to uneven land surfaces. Additionally, more land is able to be irrigated with a sprinkler system since less water is required to sufficiently raise a greater area of farmed crops more frequently than would be made possible using flood irrigation. Nonetheless, while greater efficiency in irrigation methods leads to the irrigation of more land and higher water consumption, more crop cuttings per season yield higher earnings and can directly benefit farmers and ranchers.

Another consequence of irrigation conversion is the loss of hydrologic services provided by traditional flood irrigation, which is actually less hydrologically consumptive than more efficient irrigation systems. Flood irrigated fields and unlined irrigation diversion structures are known to have great influence in maintaining vital wetland ecosystems and municipal groundwater supplies [30–32]. In some cases, flooded fields and unlined diversion ditches are the largest sources of incidental shallow aquifer recharge, which helps maintain late-season return flows and provides water for many municipal and ecological needs [30–33]. Greater dependency on groundwater for domestic and municipal needs and the mass conversion to more efficient irrigation systems throughout the state of Montana are two examples of potential sources of water shortage that must be addressed to meet future human and environmental demands.

Water Shortage and Flood Mitigation in Montana

Conservation outreach, education, grant programs, as well as water right transfers (e.g. from retired agricultural uses to instream flow or "Murphy's" rights) are some of the methods being used in Montana to try to sustain adequate water availability for water users, and maintain suitable streamflow levels relied on by riparian ecosystems and endangered fish populations [34–38]. The Montana Association of Floodplain Managers and Department of Environmental Quality (DEQ) recognize the roles that floodplains have in storing flood water and protecting homes and communities from major flood events [39]. The DNRC, Montana Disaster Emergency Service, Federal Emergency Management Agency, and the U.S. Army Corps of Engineers worked together to establish the Montana Silver Jackets Flood Risk Reduction Charter, which aims to manage and reduce flood risk while protecting the natural and beneficial functions of Montana floodplains [40]. Montana state agencies are also prioritizing alternative and more integrated methods of water storage that maintain the integrity of natural systems while meeting social and ecological demands for water. One of the most important tools for meeting future water demands in Montana in the face of a changing climate, as expressed by the DNRC, is the development of new storage projects that can capture early spring runoff to meet late-summer demands – a feat that is limited by cost, the availability of suitable storage locations, the need to mitigate environmental impacts, and limited legal and physical access to storable water [10].

The DNRC's 2015 Montana State Water Plan (MSWP) contains 68 recommendations "intended to guide state water policy and management over the near,

intermediate, and long term bases" [10]. According to the DNRC, fulfillment of all 68 recommendations in the MSWP would resolve several of the state's most pressing and complicated water issues, including drought preparedness at the watershed scale and supplying water to serve the needs of a growing population, as well as the state's renowned ecosystems and natural habitats. As evidence of the long term environmental impacts to constructing traditional storage structures (i.e. dams) continues to come to light, the MSWP highlights alternative methods of retaining water that enhance natural systems and improve resource availability for human use [41].

One alternative the DNRC has been exploring is the use of infiltration galleries that channel flood water or water from a historic irrigation right into a groundwater aquifer to augment groundwater consumption and artificially recharge shallow aquifers [42–44]. Another alternative to traditional water storage and flood mitigation being explored by the DNRC is the use of natural storage, which includes existing natural systems like floodplains, riparian areas, and wetlands that act to absorb excess floodwater, slow runoff, and promote groundwater recharge and the slow release of water back into a surface water system [10,44,45].

When protected or enhanced, natural storage systems can be effective tools for increasing water retention in basins facing water shortage or flood, and raising water tables in incised river systems [46–49]. The strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecological values and functions while providing associated benefits to human populations is referred to as *natural infrastructure* [49]. The installation of structures that mimic the ecological services

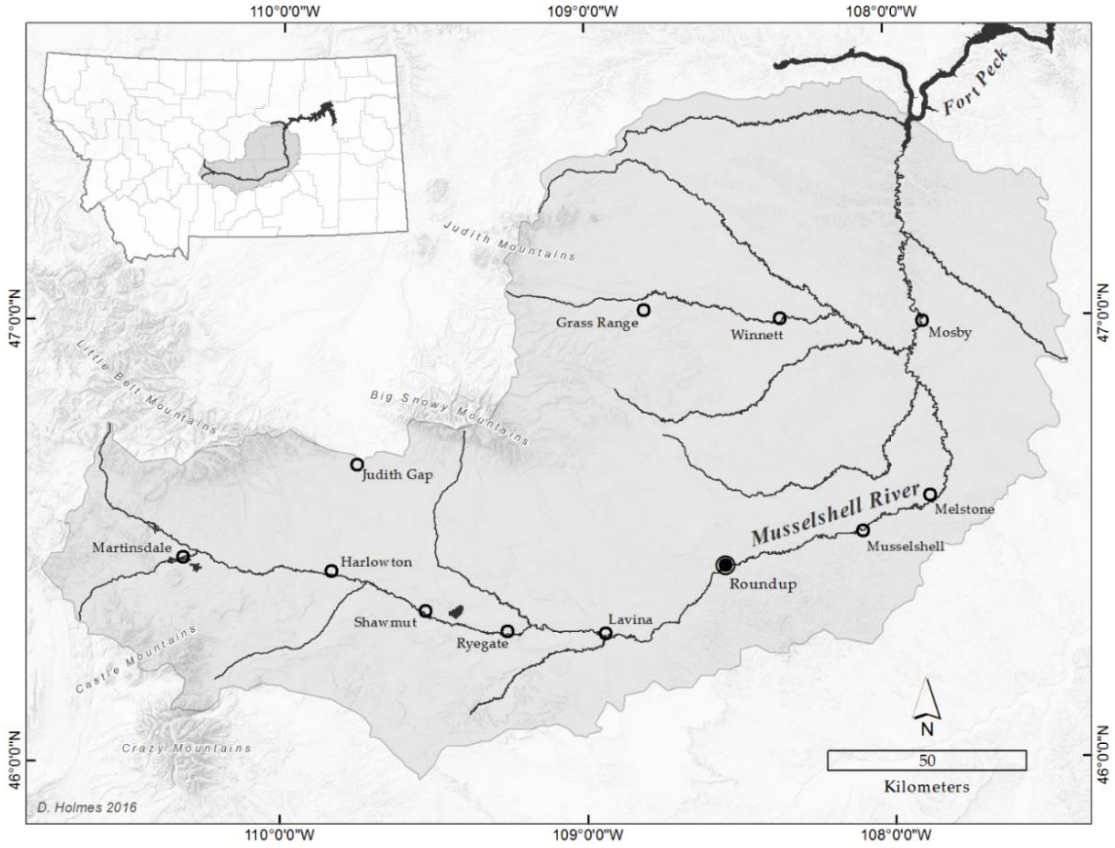
provided by beavers, wetland restoration, or the reconnection of incised streams to their floodplains through the removal of retired roads or railroads are all examples of natural infrastructure methods of promoting water retention to meet human and environmental needs. One of the short term MSWP recommendations intended to facilitate the integration of natural storage to help meet Montana's water demands is the development of a pilot project quantifying natural storage capacity. More specifically, DNRC officials have communicated the need for a method that estimates the water storage potential of floodplains to aid in the assessment of natural storage feasibility. The research outlined in this paper addresses this need by developing a geospatial method for identifying prospective natural storage implementation sites, and examining the water storage potential of an identified site located on a portion of the Musselshell River (MSR) floodplain in central Montana.

Case Study: The Musselshell River Basin

The MSR is 550 kilometers (km) long tributary of the Missouri River which is fed by snowmelt from the Crazy, Littlebelt, Castle, Big Snowy, and Judith Mountains (Figure 1). The Musselshell River Basin (MSRB) has been identified as a high-priority area for the implementation of alternative methods of water storage and the assessment of natural water storage potential due to the classification of the MSR as chronically dewatered, along with the unprecedented flooding of the MSR in 2011 and 2014 [50]. Flooding in the MSR has disturbed the connectivity between the river channel and its floodplain, leading to higher flow velocities, streambed incisement, rapid abandonments of stream

reaches (avulsions), and a general decrease in the storage capacity of its floodplains [51,52]. Residents of the MSRB and members of the Musselshell Watershed Coalition

Figure 1.1. Map of the Musselshell River Basin, the Musselshell River and its largest tributaries, and the Basin's most populous towns. The Musselshell River flows west to east from the confluence of its North and South Forks and into the Fort Peck Reservoir.



(MWC) have engaged in a collective effort to unify basin-wide interests geared towards reducing the risk associated with water shortage and extreme flood events. These collective efforts include undertaking large-scale stream restoration and rangeland improvement projects. In recognition of their continued efforts to improve their

watershed to meet human and environmental needs through basin-wide collaboration, the MWC earned the Montana Wetland and Watershed Stewardship Award in 2015 [53,54]. The MWC has fostered an impressive network of volunteers who have donated nearly 200 hours toward efforts "to make more informed water management decisions along the MSR" [55]. MWC member insights into the water storage and management needs of MSRB residents were integral to study site selection, and the development and success of this research project.

The MSRB was selected as a broader study region due to the impressive watershed-scale efforts to improve the reliability of water supplies using a variety of methods. Furthermore, this area was selected because of its reduced floodplain storability following the 2011 flood and the willingness of the MWC to include Montana's state agencies and academic institutions in its participatory governance structure. While there are several studies that have attempted to quantify floodplain or wetland water storage potential, the development of a timely and cost-effective method of estimating floodplain water storage capacity for use in a water management setting remains a question that needs further research [56–59].

Study Intent

The intent of this study is twofold. First, this research addresses one of the short term natural storage-related recommendations listed in the DNRC's MSWP through the development of a cost effective and timely geographic information science (GIS) –based model for identifying potential off-stream sites that may be capable of supporting natural water storage. Secondly, this study develops a method for quantifying the natural storage

capacity of a portion of MSR floodplain using geospatial techniques, and a flood inundation model customized for use along the MSR. This paper details the process of selecting a study site, the sources and parameters of the data used as model inputs, the process of quantifying the storage potential of the selected study site, the results of this pilot quantification method, and concludes with a discussion of result implications, application, and limitations.

CHAPTER 2

LITERATURE REVIEW

What is Natural Infrastructure?

Climate change is projected to affect the quantity, quality, and timing of water availability in Montana, including a shift toward earlier spring runoff and more winter precipitation as rain [3,10]. In 2015, Montana Governor Steve Bullock reaffirmed the need to mitigate the impacts of future droughts by identifying new locations for water storage and sites where water can be stored more efficiently [4]. Natural or green infrastructure, as defined by the World Resources Institute, is the "strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecosystem values and functions while providing associated benefits to human populations" [49]. In the 2015 MSWP, the Montana DNRC explains that *natural water storage* is the use of existing natural systems (riparian areas, floodplains, wetlands) to slow runoff and promote groundwater recharge – and storage – and the slow release of water back into a surface water system [10]. Capon et al. (2013) stress that riparian ecosystems are hotspots for climate change adaptation, and that the proactive reformation of conservation and natural resources management practices can be made more robust by ecosystem-based approaches to climate adaptation [60,61]. The California Roundtable on Food and Water Supply (CRFWS) summarized seven recommendations for the creation of a more effective "water retention model" that could provide a more diverse set of water management strategies to increase regional self-sufficiency [62]. CRFWS

recommendations promote the consideration of natural systems to better mitigate drought in the resource management process. The precepts of natural infrastructure methods of water storage as summarized by CRFWS are shown in Table 2.1.

Table 2.1. CRFWS recommendations to promote natural water retention [62].

From	*To*	
Uniformity	Diversity	*A diversity of storage* scales, methods, and locations is important for maximizing short- and long term resiliency in the system. Effective storage will be place-based and flexible, acknowledging varying needs, resources, and solutions available in different regions.
Resistance	Resilience	*Work in concert* with natural watershed dynamics and ecosystem functioning to maintain water supply for food production and healthy ecosystems in the face of environmental change.
Bathtub	Sponge	*Increase retention in the soil* profile in upper watersheds, farms, and throughout the watershed. Annually renewed water in naturally functioning watersheds and meadows is stored in soils, vegetation, and shallow groundwater, and in transit via flowing rivers, creeks, springs, lakes, and other surface water.
Centralized	Distributed	*Capturing water* in many places not only can add meaningful capacity when considered in aggregate but is more likely to reduce costs, increase local control, and benefit local farms and food security. Use every possible option for holding water - cisterns, bladders, engineered underground storage, on-farm ponds, seasonal wetlands, soils, regional ponds, larger reservoirs.
Nodes	Network	*Re-pattern the flow and distribution* of water in the landscape to integrate water capture, conveyance, and storage connectivity to maximize their discrete and collective opportunities. Increase storage for short- and long term use by developing distributed storage sites of varying scales and greater connectivity.
Runoff	Infiltration	*Slow down the water cycle* to temper the intensity of big rain events, capture excess water for land use, and filter the water to remove sediment and contaminants. Implement land management approaches that slow runoff and increase infiltration. Integrate water quality objectives into these approaches.
Use	Reuse	Storage systems can enhance tailwater capture, *reuse*, and infiltration, and contribute to new supplies on location or downstream.
Noun	Verb	*Thinking of storage as a process*, and not just a series of reservoirs that can help us better achieve water storage and distribution goals.

These recommendations emphasize the need for a shift in our concept of water storage from of series of traditional structures (i.e., concrete dams) toward viewing water storage development as a dynamic practice that benefits from the consideration of natural storage *processes*. The terms *natural infrastructure* and *natural storage* will be used interchangeably in this paper and will refer to the process of enhancing or protecting natural systems that can be used in conjunction with or as alternatives to traditional storage structures to promote ecological vitality and aid in the retention of water to meet human *and* environmental needs.

Natural infrastructure echoes the changing water paradigm of the 21st century outlined by Gleick (2000), which emphasizes the incorporation of ecological values into water policy, a shift away from a primary reliance on finding new sources of water, and the prioritization of non-structural alternatives to meet demands [63]. For instance, built structures like dams reduce the availability of water for ecological needs while increasing seasonal volatility in water supply [41,64]. In Montana, weirs in the Yellowstone River have impeded upstream migration of native fish species for over 100 years, including the endangered pallid sturgeon [65]. In some cases, dams and other diversions of river water can also reduce vegetation health and water fowl populations [66].

In a groundbreaking and controversial study valuing the world's ecosystem services, Costanza et al. (1997) estimated that 38% of our global natural capital comes mainly from terrestrial forests and wetlands [67]. Butchart et al. (2005) claimed that wetlands in particular provide considerable ecological services relating to food and

freshwater provisioning, climate regulation, nutrient cycling, and cultural well-being [47].

From the mid-1800s through the 1970s, wetlands in the United States were largely viewed as wastelands in need of improvement, and federal policy during that time allowed "swamp and overflow lands" to be drained and converted to agricultural land. However, in 1977, President Jimmy Carter recognized that important wetland functions (e.g., maintenance of surface and groundwater quality, flood control, and nutrient and pesticide filtering) are all services that benefit the public [68,69]. Executive impetus in the federal government to protect wetlands continued in 1989 when George H.W. Bush established the "no net loss of wetlands" policy, which aimed to maintain or increase the total acreage of wetlands in the U.S. in the face of progressing economic development [70,71]. Throughout the U.S., protection, enhancement, restoration, and construction of floodplains and wetlands have been considered as alternatives to more expensive and highly technical methods of improving municipal and environmental water quality and availability [49].

For example, in the late 1990s, the City of New York was able to protect its water quality by conserving forests and protecting wetlands in the 5,180 km^2 Catskills watershed at a cost of $1 billion [48]. In contrast, the construction of a new water filtration plant would have cost an estimated $6 billion, not including annual maintenance. The watershed preservation program boosted the local economy and income of rural farmers and forestland owners while encouraging ecotourism [48]. In another case, researchers at the Bureau of Land Management found that riparian

restoration was three times more cost effective than lagoon storage and mechanical chillers at reducing temperature load requirements to required levels in the Rogue River Watershed near the city of Medford, Oregon [72]. In Minnesota, studies on the Mustinka subbasin suggest that restored wetlands in the region have considerable potential to increase water storage (i.e., restoration of drained and farmed wetlands were associated with up to a 63% and 50% storage increase, respectively) [73].

How is Natural Infrastructure Related to Water Storage and Ecological Resilience?

Because wetlands and floodplains serve similar hydrologic functions, it is useful to differentiate between the two when discussing natural water storage and infrastructure. Floodplains can be defined as streamside lands that are periodically inundated by surface floodwater, and are capable of acting as natural water sponges that store and slowly release water after large events [74]. Alternatively, wetlands are areas where soil is inundated by surface or groundwater regularly enough that the prevalent vegetation community and wildlife is adapted for life in saturated soils; like floodplains, wetlands store precipitation and surface water then slowly release the resource into associated surface and groundwater resources during dry periods or drought [74,75]. Thus, floodplains may be more suitable than non-floodplains to undergo natural infrastructure implementation due to their periodic inundation by water.

Wetlands provide three primary hydrological functions, including floodwater attenuation, groundwater recharge/discharge, and sediment retention [76]. One of the largest problems facing floodplain managers is streambed downcutting or incision, which

prevents floodwaters from spilling out onto a floodplain [77]. Streambed incision interrupts the ecologically vital lateral connectivity of a stream to its floodplain and can result from a number of events, such as road or railroad construction, high streamflows, channel straightening, and loss of riparian vegetation – all of which lead to a reduction in groundwater recharge and an increase in surface runoff [78–82]. Incisement can also lead to water quality degradation and the drainage of water away from and lowering of water tables below wetlands [83,84].

Previous research on the feasibility of wetlands and other natural infrastructures to attenuate floodwater and treat waste water has yielded mixed, though generally promising results [45,47,85–88]. The Montana DNRC considers natural and mimicked beaver dams in particular to be potentially viable forms of natural infrastructure [89]. Studies on such structures have shown they can improve water quality and slow down water flow, generate riparian vegetation, enhance channel stability and wetland hydrologic processes, deliver ancillary benefits to fish populations, and provide significant and cost-effective natural storage opportunities [90–96].

In Montana, efforts to address stream incisement in Odell Creek using artificial beaver dams (or beaver mimicry structures) were successful in elevating streambeds, and contributing to greater channel and wetland habitat complexity [46]. Based near Twisp, Washington, the Methow Beaver Project relocated beavers seen as a hindrance by private landowners to more suitable riparian areas in order to re-establish active colonies, restore key watershed processes in streams, and adapt to a changing climate by offsetting snowpack loss in the Methow River sub-basin. In their first seven years, the project's

relocated beavers and their dams have added 260 hectares of wetland habitat, and 6 hectares that have stored a total of 246,000 m^3 of water [97].

In agricultural regions, interflow and percolation of water from flood irrigation has been shown to be critical to the existence of many wetlands in the western U.S. [26–28,33]. Similarly, some wetlands, like those enhanced by the installation of beaver mimicry structures or beaver relocation, can contribute to late-season return flows and aquifer recharge in agricultural regions where reliance on more efficient sprinkler irrigation systems reduces streamflow and groundwater recharge [32,98–101]. Public and private interest in using beaver mimicry structures to address water shortage at local and regional scales appears to be accelerating in Montana [102]. Still, before natural infrastructure projects can be spearheaded by the DNRC, the agency has called for the development of a method for quantifying the water storage capacity of potential natural storage sites which is intended for use by natural resource managers in the state.

How Have Other Studies Quantified Wetland and Floodplain Water Storage Potential?

Quantifying how much water can be stored by natural infrastructure methods has been a key question for water planners in Montana [10]. While there are several studies that have attempted this, the development of a timely and cost-effective method of estimating wetland and floodplain water storage capacity that is intended for use by governmental water managers remains a question that needs further research. Specifically, the development of a method for estimating the physical storage capacity of wetlands or floodplains below the ground surface and above groundwater aquifers in a way that can be efficiently employed by government agencies and private landowners has

yet to be accomplished. For example, recent attempts to model natural water storage have done so by either isolating the dominant processes influencing wetland hydrology, calculating the water storage capacities of surficial depressions in isolated wetlands, calculating the volume of space between the ground surface and the elevation where water begins to spill out of wetland, or treating storage potential as the volume of floodwater associated with different events that would inundate different floodplain extents. However, these attempts fall short in offering both a method for identifying potential natural infrastructure sites and a method that treats natural storage as the physical volume of space that is available to store water between a wetland or floodplain ground surface and the groundwater table. Additionally, the methods described in more detail below appear to be intended to address primarily hydrologic research-related inquiries rather than the resource planning and management needs this research seeks to attend to.

Krasnostein and Oldham (2004) developed a conceptual bucket model to predict wetland water storage to Loch McNess in Perth, Western Australia [56]. The model treated various components in a system (i.e., catchment, groundwater, surface water) as individual stores that, when full, cause the resource to spill over to the next bucket. The bucket approach was preferred because of its flexibility and because the complexity of its configuration could be manipulated depending on the specific wetland system being modeled. In this case, bucket water storage was tracked over time using the water balance, which was calculated on a daily time-step since rainfall and pan evaporation data were collected daily. Model inputs were comprised of components that were calculated

using physically-based parameters, including: recorded rainfall, pan evaporation, soil depth and type, percentage of vegetation cover, and general topography. Physical groundwater values were considered during model calibration, which was minimal due to the inclusion of physical measurements for the components just listed.

Three approaches and a variety of bucket configurations were used to investigate the possible hydrological processes contributing to the Lock McNess water balance. When modeled as a retention basin, the water balance for the wetland was calculated as the difference between rainfall and both the potential evaporation over open water, and evapotranspiration of submerged macrophytes in the wetland. This approach overestimated the magnitude of seasonal depth fluctuations. In the catchment-wetland approach, the model added runoff from the surrounding catchment whose boundary was defined by the topography input, and no surface runoff was predicted. Simulated maximum winter water levels agreed with the maximum recorded levels, and a large summer deficit was predicted in the summer. In this case, predicted recharge from rainfall and catchment runoff was insufficient to meet the summer evaporative demands over the wetland. In the final approach an interactive local groundwater component was added to the catchment-wetland system, with a 5 m deep local groundwater bucket representing the maximum height of the water table above the wetland bed. Catchment subsurface runoff was rerouted to the groundwater bucket to represent local recharge by rainfall infiltration, and was the only input to the groundwater balance. A regional groundwater component was later added to the model in this approach, which dramatically increased the wetland water level during the first year of simulation. Annual

fluctuation in modeled groundwater storage was of a similar magnitude to the measured groundwater levels. Finally, subsurface overflow was added to the system, and simulated wetland water levels closely matched those measured in the field. After validation and calibration, this model was capable of predicting wetland levels to within 5 cm of accuracy of observed field values, and showed the dominance of groundwater contribution to wetland water balance. The authors stressed the need for validation of additional sources when defining groundwater trends in wetland systems.

Lane and D'Amico (2010) explored the use of remotely-sensed light detection and ranging (LiDAR) data in the form of a triangulated irregular network (TIN) to calculate isolated wetland surficial water storage capacity in north central Florida [58]. More than 12,500 potential isolated wetlands in Alachua County, Florida, were identified by acquiring a Landsat 7 scene of the study site and analyzing scene 'wetness' with band 5 (1.55-1.75 micrometer mid-infrared), which is very sensitive to soil water content [103]. Wetland volume was calculated using the TIN Polygon Volume model in ArcGIS 3D Analyst, which calculates volume below a given elevation plane which was calculated by averaging LiDAR-derived elevation points from around the edge of each wetland polygon. National Wetland Inventory (NWI) data acquired for the study site were used to assess the accuracy with which isolated wetlands were identified.

Isolated wetlands within the study area were found to store on average 1,600 m^3 of water per hectare. An exponential equation that accurately correlated wetland area and volume was developed, but when applied to a small independent dataset, the equation tended to overestimate volume. The authors acknowledge that interstitial spaces (i.e. soil

porosity) were not measured to establish average volume, since wetland morphology was established by LiDAR data which treated each wetland bottom as a concrete basin. The authors also emphasize that wetland volumes can be modeled quickly, accurately, and with little or no need for fieldwork when LiDAR data are available and used to incorporate basin shapes and profiles.

Vining (2002) developed a daily time-step hydrologic model using geomorphology and climatology data, as well as GIS-derived topographic analyses to simulate streamflow and calculate wetland water storage in the 498 km^2 Starkweather Coulee subbasin in North Dakota [57]. Vining defined two different types of wetlands: 1) "open" wetlands were defined as having an outlet with a spillage threshold equal to a fraction of the total volume of the open wetland without an outlet and 2) "closed" wetlands were defined as not having an outlet and did not spill out, but did gain and lose water in the same manner as the open wetlands. The model was used to simulate precipitation accumulation, snowmelt, evapotranspiration, soil infiltration, groundwater seepage, surface runoff, and streamflow. While there are thousands of wetlands in the subbasin, most of the land in the study area is owned privately and has been drained for agricultural uses. Input to the model included: United States Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) precipitation data; daily maximum and minimum temperatures; daily radiation values from 1990 – 1998; snow water equivalent; physiography, vegetation, soils (though there is no established method for handling frozen soil conditions that occur in the spring and winter), and hydrologic characteristics of the study area; topography and elevation data from 10 m digital elevation models

(DEM); and daily streamflow data during ice free months. Wetland surface areas and volumes were computed using GIS tools, with total wetland volume for the subbasin estimated to be just over 83,876,640 m^3**.**

The storage volumes of the wetlands were determined by calculating the difference between filled and final DEM elevations. In other words, storage potential can be considered as the volume of space between the DEM surface and the elevation where water begins to spill out of a wetland. Only the available soil water storage parameter was adjusted as it was the most sensitive model parameter. Additional assumptions about changes in other parameter values were not required, and realistic values were maintained. The DEM and wetlands model in general did not include information about the locations of roads, ditches, or other diversionary structures within the study area, a fact which Vining acknowledged as a model limitation. The lower resolution of the DEM used in the study may have also led to the inadequate representation of wetland areas and depths studied in the basin.

Grygoruk et al. (2013) compared the economic value of floodplains as storage reservoirs for excess flood water during large events to constructed reservoirs intended to serve the same purpose in the lower basin of the Biebrza Valley of northeast Poland [59]. Floodplains were treated as catchment-scale wetland ecosystems. The authors assessed the average annual volume of active water storage in the Biebrza floodplain in Poland using GIS-based techniques and quantified the monetary value of water storage in the floodplain during flooding as an important ecological service. Their floodplain water storage assessment was analyzed as a function of water levels measured by a nearby

stream gage, and the primary aim of the study's approach was to derive the relationship between average water levels of flood phenomenon and the corresponding flood extents in order to estimate storage volume. Cross sections representing variable elevations across the valley were obtained from a 30-meter DEM, and it was assumed that constant inundation levels along each cross section equal to stream gage levels could be assigned. Flood extents reflected water levels derived from the stream gage only and neglected the cross-sectional variability of the slope of the groundwater table. It was assumed that flood volumes and extents assessed for different water levels using this methodology would closely reflect average conditions. Authors acknowledged that the presence of dense summer and fall vegetation should reduce the total volume of flood water by the volume of that vegetation.

Inputs to the storage potential equation included the volume and area of flood water expected to inundate the valley for different events, a dimensionless value of porosity for a superficial layer of soil (which for peat soils was assumed to be as high as 0.85), and a critical depth to water above which the implementation of agricultural practices (e.g. mowing) is impossible due to soil saturation. The study found the water storage volume of the Biebzra floodplain to be greater in magnitude than all of the constructed reservoirs in the valley combined. Study researchers acknowledge that their approach could be improved by obtaining floodplain vegetation volume using remote sensing and hydraulic modeling techniques. In all, the average *annual* volume of active water storage in the floodplain reached 10.36 million m^3.

Why is a GIS Approach Preferred When Quantifying Natural Storage Potential?

A GIS approach is well-equipped to provide a method of storage potential calculation at large (state) and small (local) scales. The tools used in geographic approaches are effective alternatives to traditional tools and methods of information retrieval and analysis in natural storage research. These tools include remotely sensed satellite imagery or aerial photography, topographic data, legal land (e.g. township and range) surveys, land cover maps, and map shapefiles and datalayers that can include a range of hydrologic information in a spatially distributed format. In general, GIS is beneficial in allowing the remote study and analysis of large-scale natural resources and regions, and in allowing researchers the ability to study sites and regions that may be prohibitively difficult to access physically due to rough terrain or legal restrictions [104].

Additionally, it is possible to perform GIS analysis using open-access applications (e.g. QGIS, R Studio) that have nearly the full range of functionality as more popular but costly GIS platforms (e.g. ArcGIS), so long as the user is experienced in the relevant programming language of the applications in question. The most notable benefit of using a GIS approach to natural infrastructure research is that spatial data crucial to water storage studies are often available to the public for free.

In the MSWP, the DNRC has recommended working with stakeholders to develop a pilot project to quantify natural storage capacity in smaller watersheds before the implementation of natural infrastructure [10]. A GIS approach to estimating the natural storage potential of a floodplain or wetland from a physical rather than hydrologic

perspective allows for the development of a time- and cost-effective storage model that can be replicated by state officials and, in some cases, private stakeholders.

What Elements Are Necessary in the Development of a GIS-Based Natural Storage Quantification Model?

Elevation Data

Until recently, the spatial resolution of commonly available digital topographic data for the U.S. were insufficient to map geomorphic features (including wetlands and floodplains). LiDAR technology emerged in the 1960s and was widely used in meteorological research to address the shortfalls inherent in the radar imaging of clouds and atmospheric analysis [105–107]. Meteorological LiDAR systems measure atmospheric characteristics by determining the travel time of laser pulses (hundreds of thousands per second) to features in the sky and back to the sensor. Today, aircraft mounted LiDAR systems are able to provide topographic data with superior vertical accuracy and horizontal resolution, which have expanded its applicability to ground-based research. The generation of DEMs and digital surface models make LiDAR especially valuable for forestry and vegetation analyses, while the ability to filter and remove the influence of vegetation canopies makes LiDAR especially useful in wetland and floodplain research applications [108–111]. Use of LiDAR data in wetland studies eliminates the need for *in situ* laser transects and costs associated with field visits [58,109,112–114]. Still, acquiring imagery for large-scale (watershed-wide) projects in a timely manner requires an aircraft, and extensive data storage is a costly process. However, publically-available LiDAR imagery is becoming increasingly available for

many areas within Montana, making this technology more accessible to the public and to researchers [115]. In Montana, LiDAR elevation data have also been particularly effective when employed in flood inundation research, human stream impact studies, and channel migration zone mapping [116–120].

Soil Data

Knowledge of physical soil characteristics is essential in the assessment of surface-groundwater interactions and processes, including those that determine the water storability of a small floodplain [121]. The United States Department of Agriculture's Natural Resource Conservation Service (NRCS) has developed the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases that are frequently referenced in studies requiring information on soil characteristics at large (STATSGO) and small (SSURGO) geographic scales, and in spatial (i.e. GIS-friendly) formats.

With a scale of 1:250,000, STATSGO data are designed for broad management uses at regional scales and were created by generalizing a variety of information. Data on geology, topography, vegetation, and climate were assembled and related to Landsat satellite imagery to create the STATSGO dataset when more detailed soil survey maps were unavailable [122]. Original STATSGO data were aggregated and made available in an ArcGIS-friendly format in 1997, and revised in 2006 [123]. In contrast, the SSURGO database is intended to address natural resource planning and management needs of landowners, townships, and counties at scales ranging from 1:12,000 to 1:63,360, and is comprised of laboratory-analyzed soil information as collected by the NRCS over the course of the last century [124]. The SSURGO database includes general land cover

classifications (e.g. floodplain, agricultural land, urban), and myriad physical soil characteristic information available for the first 150 cm of soil in a given study area, including hydraulic conductivity, available water storage, bulk density, and sand/silt/clay/organic matter content.

SSURGO data boundaries for Montana soils are reference validated using 1-m resolution NAIP aerial photography. Reference validation using updated high resolution aerial photography is considered an appropriate substitute to *in situ* 'ground truthing' in land cover analyses of areas that are either physically inaccessible, or excessively large in scale to perform field analysis in a reasonable amount of time [125]. The use of SSURGO as an input in several hydrologic models and finer-scale studies has yielded favorable results when compared with the input of STATSGO data.

For example, SSURGO soil data tends to provide overall better predictions of discharge than STATSGO when used as an input in the Soil and Water Assessment Tool [126]. Alternatively, when used as an input in the Water Availability Tool for Environmental Resources, use of SSURGO data yields better results due to the availability of certain parameters (e.g. available water storage) [127]. The use of SSURGO data has also been shown to decrease statistical error when compared to the use of STATSGO in hydrologic flood simulations of basins with varied soil texture distribution [128]. In the same study, curve numbers estimated using STATSGO soil characteristics in conjunction with National Land Cover Dataset (NLCD) data were more similar to the more favorable SSURGO-only estimates when generic land use was assumed.

Land Cover and Land Use Data

The state of Montana has over $57 billion in agricultural assets, is comprised mostly (64%) of farms and ranches, and ranks the state second in the nation for most farm land [129,130]. Implementing natural storage or converting private agricultural land to wetland requires extensive collaboration with property owners. Likewise, the search for adequate natural storage sites in such an agriculturally-centric state requires the ability to identify productive farm land/pasture at a fine scale so as to avoid the analysis of such land where the implementation of natural infrastructure would be prohibitively difficult (legally and/or hydrologically). NLCD is a widely-utilized land cover database that was first developed in 1992, and much like STATSGO, its 30-m resolution is best suited for regional applications [131].

In 2005, the Montana Department of Revenue (DOR) began developing a state-specific land cover dataset intended to provide consistent mapping of active agricultural lands in the state. The Final Land Unit (FLU) land cover classification system consists of data that are regularly updated and categorized into seven land uses: fallow, hay, grazing, irrigated (flood, pivot, or sprinkler), continuously cropped, forest (commercial or non-commercial), and commercial (e.g. gravel pits, ski areas, mines). Ground features in the dataset are primarily delineated using 1-meter NAIP aerial photography, with most classifications undergoing reference validation by DOR GIS technicians [132]. FLU data have been used extensively in complex land use and vegetation mapping of several river basins and corridors in Montana, including the Yellowstone River, and the Beaverhead-Deerlodge National Forest [133,134]. The FLU dataset also played a significant role in

the development of the Montana Land Cover Framework by improving the pasture, hay, and cultivated cropland classes [135].

Long Term Well Monitoring Data

Riparian wetlands often function as both recharging and discharging wetlands in that they receive groundwater inflow from upslope areas and feed lower elevation groundwater stores through outflow [136]. The storage of water is crucial to wetland ecology and hydrologic functions, and in many wetlands, the depth to groundwater largely controls the capacity for water storage [82,136]. Water-level measurements from observation wells are the principal source of information about the hydrologic stresses acting on aquifers and how such stresses affect groundwater recharge, storage, and discharge [82]. It is long term, systematic measurements of water levels that provide essential data needed to evaluate groundwater changes over time, develop groundwater models and trend forecasts, and monitor the effectiveness of groundwater management and protection [82].

The Montana Bureau of Mines and Geology's (MBMG) Ground Water Assessment Program (GWAP) manages Montana's statewide groundwater-level and groundwater-quality network of roughly 1,000 sites [137]. More than one-third of GWAP sites are a part of a system of long term ground water assessment and monitoring (GWAAMON) wells that are visited on a quarterly (sometimes monthly) basis for static water levels [138]. Electronic data loggers and paper recorders also record water levels, and groundwater is sampled on a periodic basis for water quality analysis and review. All data collection methods are reviewed and downloadable by the public free of charge

[138]. Potential drawbacks to periodic monitoring are that hydraulic responses to short term stresses may be missed if they occur between measurements, extreme water level fluctuations cannot be determined with certainty, and apparent water level trends may be biased by the choice of measurement frequency [82].

CHAPTER 3

NATURAL WATER STORAGE AND CLIMATE CHANGE RESILIENCY IN MONTANA: A GEOSPATIAL APPROACH

Contribution of Authors and Co-Authors

Author: Danika L. Holmes

Contributions: Conceived and designed research objectives, designed the natural storage site identification system and storage model, created and designed study maps, and wrote the article.

Co-Author: Dr. Jamie McEvoy

Contributions: Conceived and designed research objectives; guided literature review, research process, and article writing.

Co-Author: Dr. Jean Dixon

Contributions: Contributed to the design of the storage model.

Co-Author: Dr. Scott Payne

Contributions: Contributed to the design of the storage model.

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Natural Water Storage and Climate Change Resiliency in Montana: A Geospatial Approach

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Abstract: Across the globe, climate change is projected to affect the quantity, quality, and timing of water availability. In western North America, there has been a shift toward earlier spring runoff and more winter precipitation as rain. This raises questions about the need for increased water storage to mitigate both floods and droughts. Water managers in the western U.S. have identified natural storage structures (e.g., wetlands, floodplains) as valuable tools for increasing resiliency to these climate change impacts. However, quantifying the storage potential of natural structures is a key challenge. This study addresses the need for a method for estimating floodplain water storage capacity in a manner that can be used by water resource managers through the development of a model that identifies potential natural storage sites using open-source geospatial data. This model was used to estimate the storage capacity of a 33 hectare floodplain segment in eastern Montana. The result is a range of storage capacities under eight natural water storage conditions, ranging from 934 m^3 for small flood extents to 321,252 m^3 for large floods. Incorporating additional hydraulic inputs, landowner needs, and stakeholder perceptions of natural storage into this model can help address more complex questions about using natural storage structures as an ecosystem-based climate change adaptation strategy in the western US.

Keywords: water; natural infrastructure; natural storage; GIS; drought resilience; floodplain; climate change adaptation; water management.

1. Introduction

There is a global consensus among leading climatologists that human activity is leading to a less predictable and generally warmer climate [1]. Research in western North American climatology has found evidence of, and projects further shifts in, the timing of stream runoff and peak streamflow linked to increasing winter rain and

declining snowpack resulting from anthropogenic climate warming [2,3]. There is growing concern about the capacity of existing infrastructure to mitigate flood and drought risks associated with these shifts. Additionally, as the long term environmental and economic consequences of traditional storage structures (i.e. dams) are recognized, there is growing interest in alternative methods of retaining water that enhance natural systems and improve resource availability for human use [4–11].

In the western U.S., water resource managers have identified the need for increased water storage and retention as important tools for meeting future demands and responding to climate change. Recognizing the role that natural storage structures (e.g., wetlands, floodplains) play in slowing runoff and promoting groundwater recharge (i.e., natural water storage), resource managers in the case study outlined in this paper have called for the development of a project that identifies potential natural storage sites and quantifies their storage potential for the purposes of storing and retaining water for the benefit of people and ecosystems.

The intent of this study is twofold. First, this research seeks to address the need for a method for identifying potential natural infrastructure sites in a way that can be more seamlessly implemented in a resource management and planning capacity using a geographic information science- (GIS) based approach. Secondly, this study develops a model for quantifying the storage capacity of natural storage systems (e.g. floodplains, wetlands) using geospatial tools rather than strictly hydrologic programs or models. The model outlined in this research was intended to provide the ability to coarsely identify potential natural infrastructure sites and estimate storage capacity in other floodplains so that it may be used by resource managers as well as other stakeholders (e.g. private landowners, industry) with GIS technique training in other regions of the western United States. In order to improve the applicability of results in the lives of potential stakeholders, it is recommended that the methods outlined in this paper are considered in conjunction with input from community leaders, private water managers, irrigators, and other heavy water users around potential sites. This paper details the process of selecting a study site, the sources and parameters of the data used as model inputs, the process of quantifying the storage potential of the study site, and the results of this pilot quantification method. It concludes with a discussion of model limitations, result implications, and future research directions.

1.1. Natural infrastructure and the quantification of natural water storage capacity

The World Resources Institute defines natural infrastructure as the strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecosystem values and functions while providing associated benefits to human populations [6]. Natural infrastructure echoes the changing water paradigm of the 21st century outlined by Gleick (2000), which emphasizes the incorporation of ecological values into water policy, a shift away from a primary reliance on finding new sources of water, and the prioritization of non-structural alternatives to meet demands [12]. The

California Roundtable on Food and Water Supply (CRFWS) calls for a change in the way society conceptualizes water storage. Rather than thinking of storage as a traditional structure (i.e., concrete dam), storage should be viewed as the product of complex physical features, landscape dynamics, and management processes with the potential to retain and release water, along with the revolving suite of regulations that govern them [13]. This definition of storage emphasizes retaining water on the landscape and elongating the period of time that precipitation is available over the dry season. Natural water storage structures include existing natural systems like floodplains, riparian areas, and wetlands that act to absorb excess floodwater, slow runoff, and promote groundwater recharge and the slow release of water back into a surface water system [14–16].

When protected or enhanced, natural storage structures can be effective tools for raising water tables in incised river systems and increasing the retention of early spring runoff in basins facing possible floods or water shortage [6,7,17,18]. Natural infrastructure is the process of, and set of tools used in, protecting or enhancing natural systems that can be used in conjunction with or as alternatives to traditional storage structures to promote ecological vitality and aid in the retention of water to meet human and environmental needs. Restoring wetlands, reconnecting incised stream to their floodplains through the removal of retired roads or railroads, or installing structures that mimic the ecological services provided by beavers, are all examples of natural infrastructure methods of slowing runoff and promoting water retention [19–26]. Previous research on the feasibility of wetlands and other natural infrastructures to attenuate flood and waste water has yielded promising results [16,18,27–30]. Studies on beaver mimicry structures, for instance, have shown they can improve water quality and slow down water flow, generate riparian vegetation, enhance channel stability and wetland hydrologic processes, deliver ancillary benefits to fish populations, and provide cost-effective natural storage opportunities [19–23,25].

In agricultural regions, interflow and percolation of water from flood irrigation has been shown to be critical to the existence of many wetlands in the western United States [31–34]. Similarly, wetlands may contribute to late-season return flows and aquifer recharge in agricultural regions where increased use of more efficient, yet hydrologically consumptive, sprinkler irrigation systems has reduced streamflow and groundwater recharge [35–39]. Public and private interest in using natural infrastructures to address water shortage at local and regional scales appears to be accelerating in the West. Still, in states like Montana, natural resource managers are recommending the development of projects that quantify the storage capacity of potential natural infrastructure sites in order to facilitate the integration of natural storage structures to help meet future water demands [14].

Several studies have attempted to predict floodplain and wetland water storage, but the development of a timely and cost-effective method for estimating natural water storage capacity that may be used in natural infrastructure planning remains a challenge

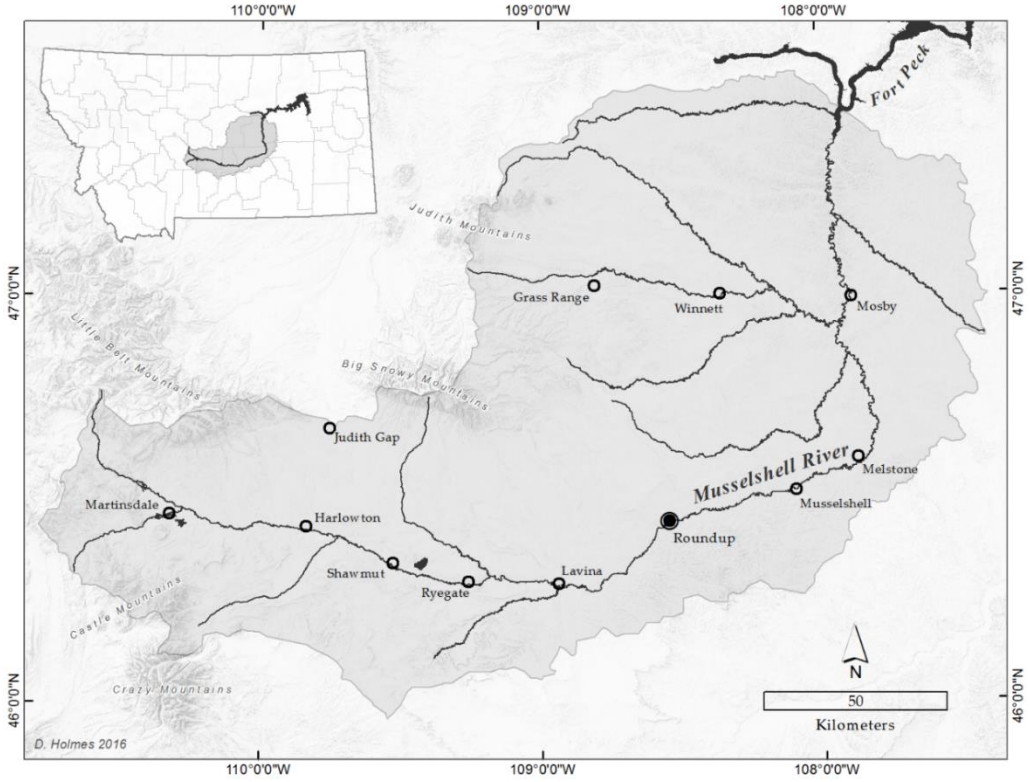
that needs further research. Specifically, the development of a method for estimating the physical storage capacity of wetlands or floodplains below the ground surface and above groundwater aquifers in a way that could be efficiently employed by government agencies and private landowners has yet to be accomplished. For example, recent attempts to model natural water storage have done so by either isolating the dominant processes influencing wetland hydrology, calculating the water storage capacities of surficial depressions in isolated wetlands, calculating the volume of space between the ground surface and the elevation where water begins to spill out of a wetland, or treating storage potential as the volume of floodwater associated with different flood events that would inundate different floodplain extents [40–43]. However, these attempts fall short in offering both a method for identifying potential natural infrastructure sites and a method that treats natural storage as the physical volume of space that is available to store water between a wetland or floodplain ground surface and the groundwater table. Additionally, the methods just described appear to be intended to address primarily hydrologic research-related inquiries rather than the resource planning and management needs this research seeks to attend to.

1.2. Case Study: The Musselshell River Basin

In Montana, the Department of Natural Resources and Conservation (DNRC) recently published the 2015 Montana State Water Plan (MSWP), which called for the development of a pilot project that quantifies the storage capacity of natural storage sites that may be suitable locations for the implementation of natural infrastructure. The Musselshell River (MSR) has been classified as a chronically dewatered stream which, along with unprecedented flooding in 2011 and 2014, makes the MSRB a high-priority area for assessing floodplain water storage potential [44–46] (Figure 1). After the 2011 flood, there was an impressive community-led watershed-scale effort to improve the reliability of water supplies using a variety of methods. Members of the Musselshell Watershed Coalition (MWC) were willing to consider natural storage structures as flood and drought mitigation options. Furthermore, they were willing to include Montana's state agencies and academic researchers in the MWC participatory governance structure.

The MSR is a 550 kilometer (km) long tributary of the Missouri River, and is fed by snowmelt from the Crazy, Little Belt, Big Snowy, and Judith Mountains. The MSRB covers nearly 25,900 km^2, and elevations in the basin range from over 2,800 meters (m) in the Crazy Mountains to roughly 610 m at the mouth of the MSR. The MSR drainage can be divided into a coldwater zone in the Upper Basin, a transitional zone in the middle portion of the basin, and a warmwater zone downstream of Roundup. Between 1928 and 2009, over 42.5 million fish – including 27 million rainbow trout – were stocked in the MSR watershed by Montana Fish, Wildlife, and Parks (FWP) [47]. Despite severe issues related to chronic dewatering, high temperatures, and poor water quality, the FWP reports that the MSR's warmwater zone contains a nearly intact native fish

Figure 1. Map of the Musselshell River Basin, the Musselshell River, its largest tributaries, and the basin's most populous towns. The Musselshell River flows west to east from the confluence of its North and South Forks and into Fort Peck Reservoir.



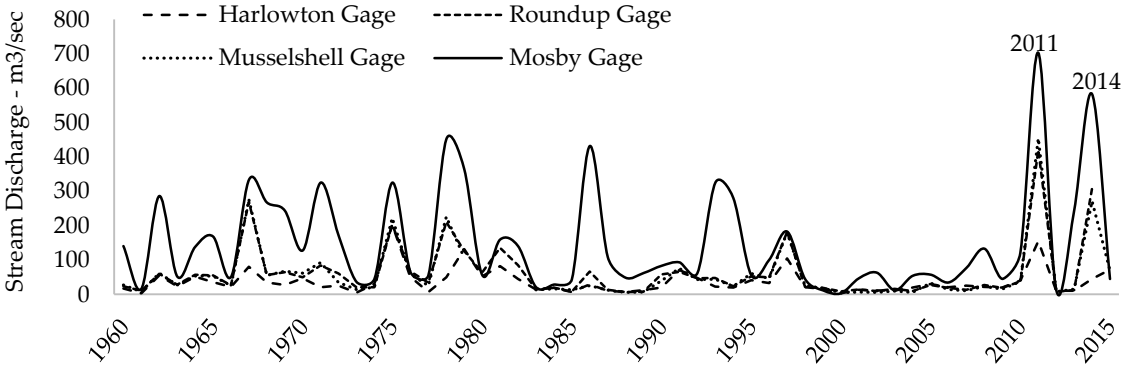
ecosystem and at least 31 species of fish. However, the fishery is impaired in the warmwater zone due to erratic discharge and the presence of diversion dams. The FWP recommends a minimum streamflow of 2 cubic meters per second (m^3/s) year round in the warmwater zone of the MSR to maintain the fishery [47].

With a population of approximately 10,000 residents, the basin encompasses some of the most rural land in the United States. Like most rural communities in Montana, those residing in the MSRB rely heavily on agricultural activities for their livelihoods, with 31,500 hectares (ha) of land being irrigated annually. The three largest reservoirs in the MSRB have a combined capacity of 132,001,030 m^3. Seven U.S. Geological Survey (USGS) stream gages in Martinsdale, Harlowton, Shawmut, Lavina, Roundup, Musselshell, and Mosby monitor stage and discharge data along the MSR. The development of roads and railroads, along with numerous flood events, have caused the MSR to become disconnected from its floodplain in many places. This has led to higher stream flow velocities, streambed incisement, rapid abandonment of stream reaches (i.e., avulsions), and a general decrease in the storage capacity of its floodplains [45,48].

Beginning in the late 19th century, a series of infrastructure projects transformed the MSR's course. The construction of the Montana (later the Milwaukee) Railroad in 1895 affected 333 km of the MSR, which was shortened and straightened to minimize the length of track and the need for bridges [45,49]. Over 140 meanders were shortened or cut off from the river, and a total of 56 km of meander length above Melstone have been isolated by the abandoned Montana Railroad [45,50]. The railroad also reduced channel access to the historic MSR floodplain, leading to further river straightening and streambed incision, higher flow velocities, and lower residence time of water in the basin [45]. Though Montana FWP identified nearly 500 km of the MSR as chronically dewatered, the river normally floods in the spring when flow typically peaks at 11.5 m^3/s at the Musselshell gage.

Although the MSRB experiences regular flooding, an unprecedented extreme event took the basin by surprise on May 23, 2011. In the spring of 2011, the Mosby stream gage read 703 m^3/sec, the highest streamflow measurement recorded by USGS stream gages on the MSR (Figure 2). Above average snowpack coupled with extreme precipitation events that spring produced the largest flood recorded in the MSRB. The 2011 event was estimated to have a recurrence interval of 157 years [45]. Following the 2011 flood, a report published by the River Assessment Triage Team (RATT) detailed channel-wide damage resulting from the flood, as well as best management practices in the midst of ongoing landscape and river course instability [45].

Figure 2. Musselshell River annual peak streamflows as recorded by four USGS stream gages between 1960 and 2015 [51–54]. Gages are listed in order of geographic position in the Musselshell River Basin, with Harlowton located in the Upper Basin, and Mosby located in the Lower Basin.



According to the RATT report, the 2011 event caused 59 avulsions and the net loss of 28 km of channel, or 8% of the river's length. The RAT team also reported severe bank erosion, channel incision, 31 complete breaches of the railroad grade, extensive irreparable irrigation and diversion structure damage, road damage, floodplain erosion, and widespread cottonwood seedling deposition. Though there was considerable damage following the 2011 flood, the ensuing widening of the channel is expected to

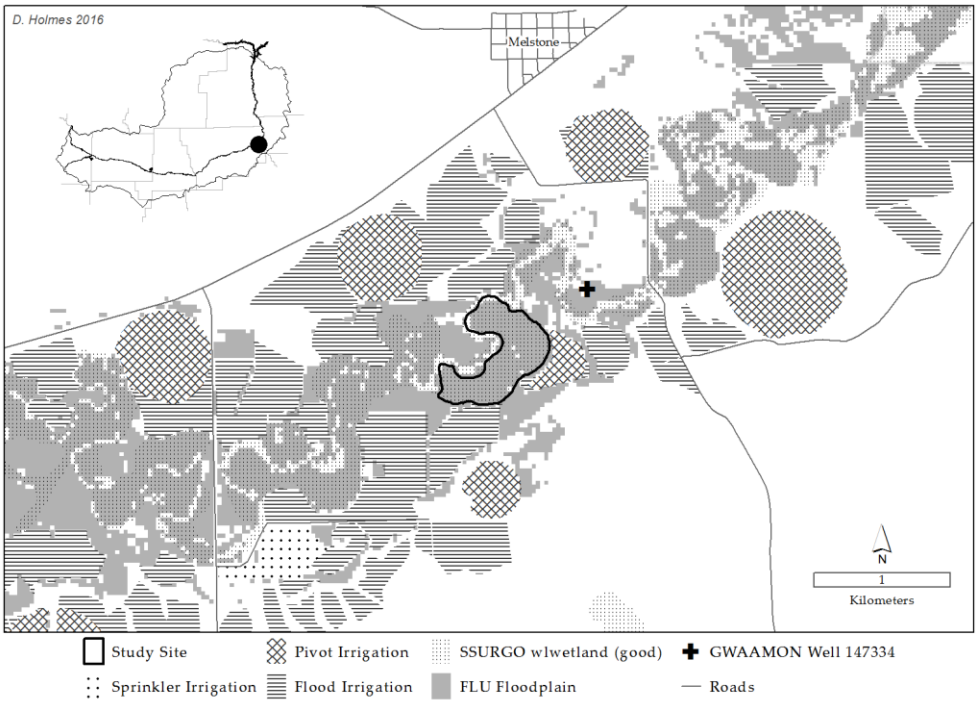
strongly influence fish habitat, with avulsions potentially playing an important role in improving the prairie stream and riparian ecosystem [47]. Another major flood event of similar magnitude to the 2011 event struck the MSRB in 2014.

In the aftermath of these unprecedented floods, residents of the MSRB and members of the MWC have engaged in a collective effort to reduce the risks associated with water shortage and extreme flood events. The MWC has fostered an impressive network of volunteers who have donated nearly 200 hours toward efforts "to make more informed water management decisions along the MSR" [55]. Part of this project's research process involved talking with MWC members to gain insight into the water storage and water management needs of basin residents. Specifically, MWC facilitators and coordinators recommended the selection of a preliminary natural storage potential study site near Melstone, Montana, due to the heightened level of destruction of this area following the 2011 flood. Furthermore, this area is especially prone to water shortages.

1.2.1. Selected Study Site

A study site with an area of 33 hectares (ha) was selected based on a set of site selection criteria (described later) that includes site classification as floodplain, high suitability of site soils to support wetland habitat, the absence of on-site transportation infrastructures, and close site proximity (422 m) to a long-term groundwater monitoring well (Figure 2). A 2 ha portion of the

Figure 3. Study site location south of Melstone, Montana, including classification characteristics of site and surrounding area.



study site is classified by the U.S. Fish & Wildlife Service's National Wetlands Inventory as freshwater emergent palustrine wetland. The study site is surrounded by productive agricultural lands that are irrigated with flood, sprinkler, or center pivot methods, and is located 1.8 kilometers south of Melstone, Montana.

2. Materials and Methods

The purpose of the model described in this section is to provide a method for 1) identifying natural storage sites that may be able to support natural infrastructures and 2) estimating the volumetric storage capacity of these potential natural storage sites. In this study, storage potential was assumed to be the physical volume of space available for the storage of water in the ground between the land surface of the study site and the groundwater table. Storage potential as it is defined in this study does not consider water that might temporarily pool above the surface during a flood event as it was assumed that water stored under the ground surface is more likely than water stored (temporarily) in above-surface depressions to contribute to late season return flows.

Research objectives were addressed using GIS techniques and open-source data. Geographic analysis was completed using ArcGIS 10.2. To quantify natural storage potential it was necessary to first identify an appropriate site using specific site selection criteria, prepare the necessary data, and analyze each of the model elements described below. In addition to developing a set of site selection criteria, finding a study area relied on personal correspondence with local water experts, policy makers, water resource managers, and residents of the MSRB who have worked on or contributed to its evolving water management structure. The collective insight of local stakeholders into the water storage and management needs in the study region was intended to guide the selection of places that were modeled to be adequate potential natural infrastructure sites, and that more closely aligned with areas that were socially perceived to have a greater need for water.

2.1 Site Selection Parameters and Storage Quantification – Model Inputs

Though this research was applied at a local level, relying on open-source data provided at a statewide scale enables the applicability of the model described in this section to other parts of the state. In other words, though a small portion of land was analyzed at this stage, the data used in the site selection process are available for the rest of Montana, and can be used to perform the same analysis in other floodplains.

After considering the guidance and input of local stakeholders, storage analysis was confined to the 450 km^2 surrounding Melstone due to the notable impacts of the 2011 flood in the area, along with the pressing water needs of Melstone-area water right holders. The specific study location was further refined according to a set of four selection criteria developed using public data and designed to facilitate the quantification of storage at a site with the greatest likelihood of successful natural infrastructure implementation. The four selection criteria that were required to identify

potential natural infrastructure sites were 1) site classification as 'floodplain', 2) proximity to a long term monitoring well, 3) high suitability of soils to support wetland habitat, and 4) the absence of built infrastructures such as roads and railroads on the site. The development of a GIS-based model to select potential sites and quantify floodplain storage relied on the availability of data informing four key elements: surface elevation, physical soil characteristics, land cover and land use patterns, and groundwater levels. Site fulfillment of each criterion was established by studying a set of public geospatial data whose parameters and general relevance in this process are described below. While the following data types (elevation, soil characteristics, land cover, groundwater well) were integral to developing a method for identifying plausible natural infrastructure sites, only the elevation, soil, and well data were used in later natural storage quantification.

2.1.1. Elevation Data

LiDAR data for the stretch of the MSR from Harlowton, Montana, to the Crooked Creek Recreation Area near Fort Peck were provided by DTM Consulting, Inc., and Applied Geomorphology, Inc., both based in Bozeman, Montana. The LiDAR database was post-processed by PhotoSciences, Inc., and included a thorough project completion report. Data for the study site were collected between May 7 and May 9, 2012 using an aircraft-mounted Leica ALS70 near-infrared LiDAR sensor. With a beam wavelength of 1064 nanometers, the LiDAR laser pulses were unable to penetrate water and had an average point density of 5.42 points per m^2 (i.e. 5.42 laser pulses per 1 m cell). NAIP aerial photographs taken in 2013 were used for reference validation of features in and around the study site.

Until recently, the spatial resolutions of publicly available digital topographic data for the United States were insufficient to map geomorphic features (including wetlands and floodplains), but LiDAR-derived DEMs are able to provide superior vertical accuracy and horizontal resolution [56]. For larger (e.g. basin) scale natural water storage research, lower resolution elevation data would suffice, but for smaller (e.g. local) scale efforts, high resolution elevation data is crucial. Aircraft-mounted LiDAR systems measure groundcover characteristics by determining the travel time of laser pulses (hundreds of thousands per second) to objects on the ground and back to the airborne sensor. The generation of high resolution DEMs and digital surface models make LiDAR valuable for forestry and vegetation analyses, while the ability to filter and remove the influence of vegetation canopies make LiDAR especially useful in wetland research applications [56–58]. Use of LiDAR data in wetland studies eliminates the need for *in situ* laser transects and costs associated with field visits [41,58–61]. Acquiring the imagery in a time-effective manner is a costly process and requires an aircraft and sizable data storage. In Montana, LiDAR elevation data have been particularly effective when employed in flood inundation research, human stream impact studies, and channel migration zone mapping [62–66]. The NRCS publicly provides statewide 1 m

resolution bare-earth LiDAR elevation data for each western state, excluding Nevada [67].

2.1.2. Soil Data

Knowledge of physical soil characteristics is essential in the assessment of surface and groundwater interactions and processes, including those that determine the water storability of small floodplains [68]. Since wetlands and floodplains often act as natural reservoirs of water and contribute to downstream return flows, this study only considered areas with soils that have a high likelihood of supporting wetland vegetation. The United States Department of Agriculture's Natural Resource Conservation Service (NRCS) has developed the State Soil Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases that are frequently referenced in studies requiring information on soil characteristics at large (STATSGO) and small (SSURGO) geographic scales, and in GIS compatible formats.

The SSURGO database is intended to address the natural resource planning and management needs of landowners, townships, and counties at scales ranging from 1:12,000 to 1:63,360, and is comprised of laboratory-analyzed soil information as collected by the NRCS over the course of the last century [69]. SSURGO provides general land cover classifications (e.g. floodplain, agricultural land, urban), and information on physical soil characteristics available for the first 150 cm of soil in a given study area, including hydraulic conductivity, available water storage, bulk density, and sand/silt/clay/organic matter content. The use of SSURGO as an input in several hydrologic models and finer-scale studies has yielded favorable results compared with STATSGO data inputs [70–72]. With the exception of a few counties, SSURGO data are published and available in every state in the US, including Hawaii and Alaska [73].

SSURGO data for the broader study region include two parameters ('wlwetplant' and 'wlshallowwet') that delineate soils with high suitability to support wetland plants and the shallow water habitats needed to sustain riparian wildlife. The SSURGO database for Melstone-area soils also includes percentage values for available water supply (α) that were used in actual natural storage estimation. The average α parameter for this study's site soils as provided by SSURGO was listed as 0.16 (i.e. 16% of the space of study site soils is available to store water).

The SSURGO data used in the development of the MSR natural storage model all assumed study site soils were at field capacity. Field capacity is the value of water content remaining in a unit volume of soil after downward gravity drainage has ceased, and under these conditions, water can be removed from soil either through direct evaporation or by plant uptake [74]. As soil dries, water movement becomes more difficult and may reach the point where the water is so strongly bound to soil particles that it can no longer be removed via plant uptake or evaporation. This condition is known as the wilting point because a plant is likely to lose turgor and wilt if the soil is not replenished with water [75]. SSURGO offers some physical characteristic data for

soils that have reached wilting point, however those data were excluded from natural storage simulation in this study as it was assumed the input of surface water to site soils at wilting point would quickly be removed by plants until the soil reached field capacity. Additionally, drier conditions are conducive to water being held in soil rather than the slow release of the resource.

2.1.3. Land Cover and Land Use Data

Roads and railroads have the potential to disrupt lateral connectivity in streams [76]. In this study, transportation structures were identified using the Montana Spatial Data Infrastructure's Transportation Framework, and the analysis of areas interrupted by such structures was avoided as such sites were considered poor natural infrastructure sites. The Transportation Framework provides GIS shapefiles for rural roads, interstates, ramps, bridges, trails, and railroads. The database is continually updated and provides the best possible coverage of transportation structures for the state of Montana.

The state of Montana is comprised mostly of farms and ranches which, at 243,000 km^2, ranks the state second in the nation for most agricultural land [77,78]. Maintaining or enhancing existing natural storage structures or converting private agricultural land to wetland requires extensive collaboration with property owners. Likewise, the search for adequate natural storage sites in a predominantly agricultural state requires the ability to identify productive farm land/pasture at a fine scale so as to avoid the analysis of agricultural land. In this case, the presence of active irrigation operations would significantly impact the flow of water through a hydrologic system and compromise the collection of hydrologic data. Additionally, implementing natural infrastructure on irrigated land that doubles as a point of use in an active water right would be prohibitively difficult.

In 2005, the Montana Department of Revenue (DOR) began developing a state-specific land cover dataset intended to provide consistent mapping of active agricultural lands in the state. The Final Land Unit (FLU) land cover classification system was used as the primary landcover database in this study, and consists of data that are regularly updated and categorized into seven land uses: fallow, hay, grazing, irrigated (flood, pivot, or sprinkler), continuously cropped, forest (commercial or non-commercial), and commercial (e.g. gravel pits, ski areas, mines). Ground features in the dataset are primarily delineated using 1-meter (m) resolution National Agricultural Imagery Program (NAIP) aerial photography, with most classifications undergoing reference validation by DOR GIS technicians [79]. FLU data have been used extensively in complex land use and vegetation mapping of several river basins and corridors in Montana, including the Yellowstone River and the Beaverhead-Deerlodge National Forest [80,81]. FLU data also played a significant role in the development of the Montana Land Cover Framework by improving the pasture, hay, and cultivated cropland classes [82].

The two most important methodological considerations addressed by incorporating land cover information were the identification of land classified as undeveloped floodplain, and the identification of irrigated land. Study site selection of land classified as 'floodplain' was important due to the regularity with which land close to main channels tends to flood. As previously mentioned, understanding study site proximity to irrigated land is also important since the use of efficient irrigation methods is known to deplete groundwater supplies and, therefore, compromise well-derived data collection [83]. These factors are important to consider in order to assess natural water storage potential. Some western states have invested resources into developing state-specific land cover databases similar to Montana's FLU dataset, and the USGS's National Land Cover Database provides national 30-meter resolution land cover information [84].

2.1.4. Long Term Well Data

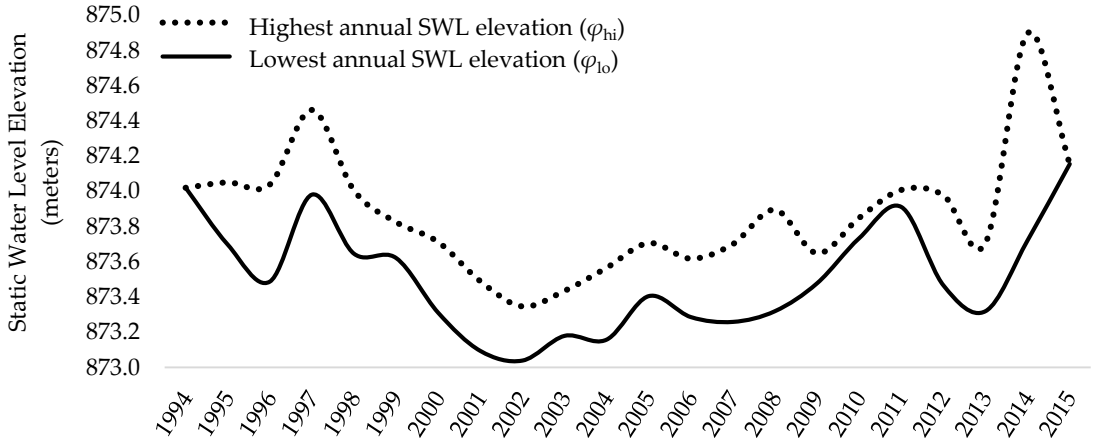
Riparian wetlands often function as both recharging and discharging reservoirs of water in that they can receive inflow from and provide recharge to groundwater sources [85]. The storage of water is crucial to wetland ecosystem vitality. In many wetlands, the depth to groundwater largely controls the capacity for water storage [85,86]. Groundwater table measurements from observation wells over time are the principal source of information about the hydrologic stresses acting on aquifers and how such stresses affect groundwater recharge, storage, and discharge [86]. It is long term, systematic measurements of groundwater levels that provide essential data needed to evaluate temporal groundwater changes, develop groundwater models and trend forecasts, and monitor the effectiveness of groundwater management and protection [86].

The MBMG's Ground Water Assessment Program (GWAP) manages Montana's statewide groundwater-level and groundwater-quality which consists of approximately 1,000 sites [87]. More than one-third of GWAP sites are a part of a system of long term ground water assessment and monitoring (GWAAMON) wells that are visited on a quarterly (sometimes monthly) basis for static water levels (SWL) [88]. Electronic data loggers and paper recorders also record water levels at some wells, and groundwater is sampled on a periodic basis for water quality analysis and review. All data collection methods are reviewed and downloadable by the public at no cost [88]. Potential drawbacks to periodic monitoring are that hydraulic responses to short term stresses may be missed if they occur between measurements, extreme water level fluctuations cannot be certainly determined, and water level trends may be biased by the choice of measurement frequency [86]. The USGS's National Water Information System provides nationwide information on groundwater levels collected from over 858,000 field measurements [89].

There is one long term MBMG-controlled GWAAMON well (#147334) located near Melstone. While there are multiple GWAP wells directly surrounding the study site,

personal communication with MBMG hydrologists confirmed that information from a single GWAAMON well is more reliable and accurate because GWAAMON wells are monitored on a more regular basis. The GWAAMON well is located near the study area and was drilled on land classified as floodplain. It has been monitored for SWL (i.e. the depth to groundwater from the ground surface) and SWL elevation (φ) on a quarterly basis since April 5, 1994. Methods of measurement for each field visit are provided in GWAAMON well logs. Figure 4 shows the highest and lowest φ elevations measured for each year between 1994 and 2015 which were used in this investigation. The difference between the highest φ elevation measurements (φ_{hi}) and the

Figure 4. Highest and lowest static groundwater level elevations (φ) measured between 1994 and 2015 from GWAAMON well 147334 [90,91]. Two measurements were taken in 1994 and showed the same φ value, and only one measurement was available for 2015 at the time of data download. The SWL peaks evident in 1997 and 2014 reflect major flooding during those years. Three field visits made in 2011 occurred in the early spring (March), late summer (September), and winter (December) months, and do not reflect major flooding during that year. Low 2002 φ values reflect a statewide drought that led to Montana's designation as a disaster area [92].



lowest φ elevation measurement (φ_{lo}) recorded during that 21 year time frame was 1.8 m. In this study, the median groundwater table elevation (or φ_m) obtained for the duration of well log data was considered 0.9 m above φ_{lo} and below φ_{hi}. Groundwater table elevation was calculated by subtracting the depth to water measurements recorded in the GWAAMON well log from the elevation of the well location as shown in the LiDAR imagery.

2.2. Quantifying Storage

The natural storage potential of the selected site was calculated as:

$$S = V\alpha.$$

Here, V is the volume of ground between the study site surface (g) and the groundwater table (φ), and α is the percent volume of this space available to store water (i.e. porosity). Table 1 describes equation variables, their units, and data sources. As this process is carried out on a GIS platform, the input elevations for g and φ are in raster format, with unique values for each cell (i, with n pixels representing the study site). The site's volume represents the product of the square of raster cell resolution (R^2) (in this study's case, R is equal to 1 m) and the potential storage thickness/site volume ($g - \varphi$), such that:

$$V = (g_i - \varphi) R^2.$$

A range of storage potentials were quantified under different parameter conditions (e.g. high (φ_{hi}) to low (φ_{lo}) groundwater table elevations, or higher and lower α values). The volume of ground between the groundwater table and the study site surface spatially varies according to the φ value and g extent used, with the overall underground volume available for water storage increasing as the height of φ decreases and the area of g increases. It was assumed φ values were spatially uniform in the absence of additional data informing hydraulic gradient. The sensitivity of this storage quantification method to changes in the available water supply parameter (α) was assessed by adjusting the SSURGO-derived α parameter by 1% and 5%.

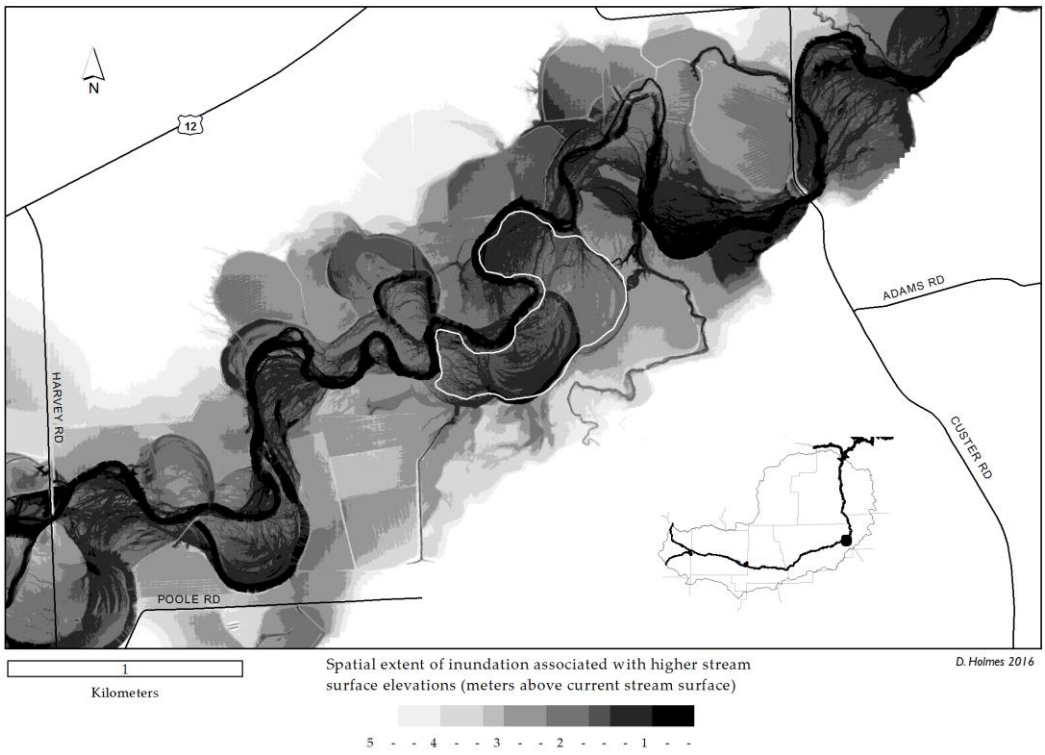
Physical storage capacities were analyzed for the study site during different flood extents. A geospatial inundation model was developed to identify different study site extents that are flooded by water when the stream surface increases in elevation by a specified amount. In this case, the inundation model simulated spatial flood extents on the Melstone study site that correlate with ten higher-than-normal MSR surface elevations (Figure 5). In this definition, 'normal' stream surface elevations are spatially but not temporally variable since they correspond with different stream elevations recorded by the LiDAR sensors during the specific dates of imagery collection.

The inundation model produced an inundation map of the study site using LiDAR elevation data and custom LiDAR cross sections of the floodplain surrounding the study site. This model first calculates the difference in vertical (z) distance between individual cells in the LiDAR imagery and the lowest z point of a cross section (i.e. the portion of stream surface intersected by a cross section) nearest to the cell. A given cell is considered to be inundated when the difference in z distance between the cell and the closest cross section's lowest z is surpassed by the modeled stream surface elevation increase. The study site was simulated to be entirely inundated when the elevation of the stream surface was 3 m above normal. A more detailed outline of inundation modeling using this method in ArcGIS is provided in Appendix A.

Table 1. Description of site storage quantification equation variables.

Variable	*Unit*	*Description*	*Source*
S	m^3	Study site natural water storage capacity.	$V\alpha$
V	m^3	Volume of ground below the site surface (g) and above the groundwater table (φ).	$g - \varphi$
g	m	Elevations of all of the points on the site surface (i.e. cells in the LiDAR site raster) that would be inundated by water when the stream surface elevation increases by a specified amount, e.g. g_3 would correspond with the elevations of the points on the study site surface that would be under water during a stream surface elevation increase of 3 m.	LiDAR elevation data
φ	m	Elevation of the groundwater table. In this study, three groundwater elevations were used to model site storage potential: a 'high' groundwater table elevation (φ_{hi}), a 'low' groundwater table elevation (φ_{lo}) and a 'median' groundwater table elevation (φ_m).	GWAAMON well 147334 (MBMG)
R	m^2	Resolution of the cells comprising the 2-dimensional g and φ rasters. Raster resolution in this study was 1 m.	Raster metadata
α	%	Percentage volume of space between the site surface and the groundwater table that is available to store water, i.e. available water supply or porosity of site soils. According to SSURGO, Melstone site soils at field capacity have an average α value of 16%.	SSURGO (NRCS)

Figure 5. Study site inundation map showing the extent of flooding associated with different MSR surface elevation increases. The site is entirely inundated when the stream surface increases in elevation by 3 m.



3. Results

The storage quantification method introduced in this paper produced a wide range of storage potentials that were linearly sensitive to changing α values. Figure 6 shows that when simulating storage potential for an increase in stream surface elevation of 3 m (i.e. an entirely inundated study site), a 1% change in α corresponded with a change in storability by ±12,000 m^3, while Figure 7 shows that a 5% change in α corresponds with a 5-fold simulated storability change of ±61,000 m^3. In simulating site storability with different groundwater table elevations, it was found that a 0.9 m increase or decrease in groundwater elevation corresponded with a storability change of ±304,000 m^3 for an entirely inundated study site. Figures 8 and 9 display the range of site storage potentials when high, average, and low groundwater table elevations are modeled with either 1% or 5% changes in α for a variety of stream surface elevation increase intervals. The lowest and highest storage potentials simulated for all conditions were 934 m^3 and 321,252 m^3, respectively. All simulated storage potentials are listed in Table 2.

While the entire study site is inundated by a stream surface elevation of 3 m, it was found that less than 2% of the study site would remain above water when stream surface elevations increase by 2.1 m. In general, higher available water supply percentages, lower groundwater table elevations, and large increases in stream surface elevations were associated with the simulated storability of more water.

Figure 6. Influence of a 1% change of α on site storability. Median groundwater elevation values (φ_m) were used as a control for groundwater level to analyze the influence of α in this model.

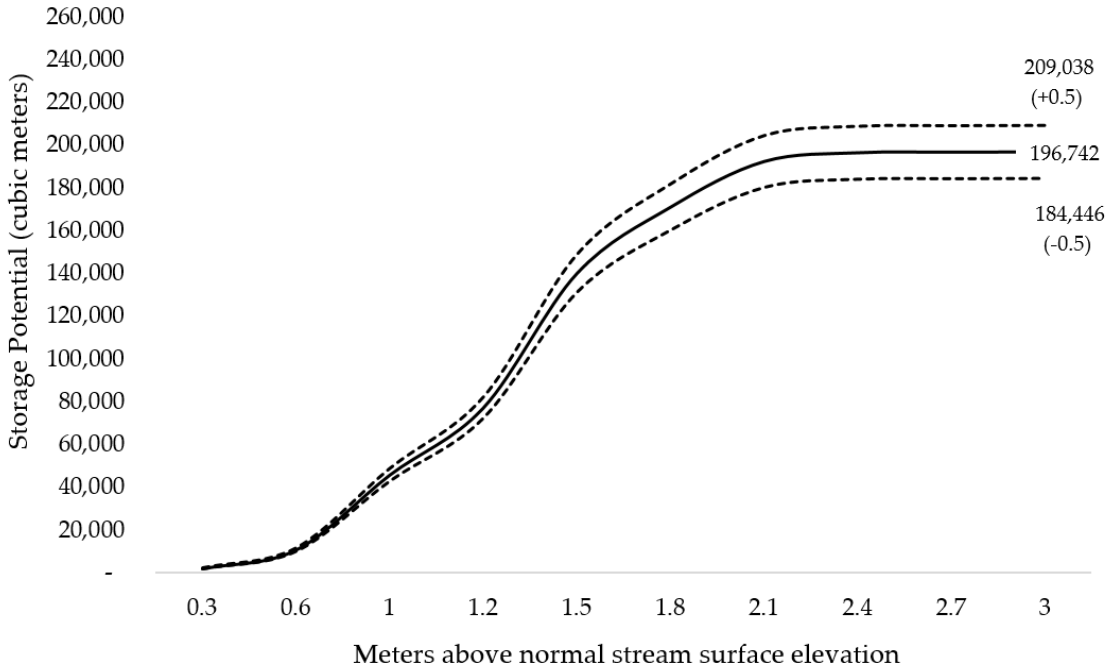


Figure 7. Influence of a 5% change of α on site storability. Median groundwater elevation values (φ_m) were used as a control for groundwater level to analyze the influence of α in this model.

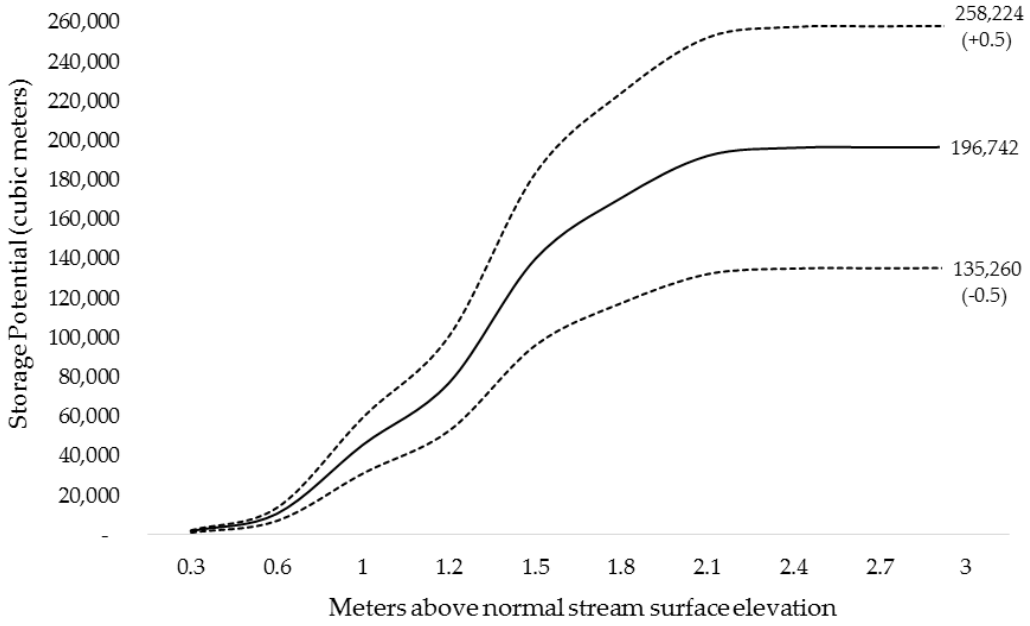


Figure 8. Graphed storage potentials simulated for 1) the observed highest (φ_{hi}) and lowest (φlo) static groundwater levels, as well as the mean (φ_m) static groundwater level taken from GWAAMON well 147334 from the last 21 years, and 2) when site soils have an available water supply value (α) of 21% (α_{21}), 16% (α_{16}), or 11% (α_{11}) (i.e. a 5% change in α). Storage potentials increase as static groundwater table elevations (φ) decrease and the available water supply of site soils (α) increase. The difference between the highest and lowest estimated storage potentials for an entirely inundated study site in this scenario (i.e. when φ_{hi}, φ_{lo}, and φ_m are considered and the difference between highest and lowest α is 10%) is 219,007 m^3.

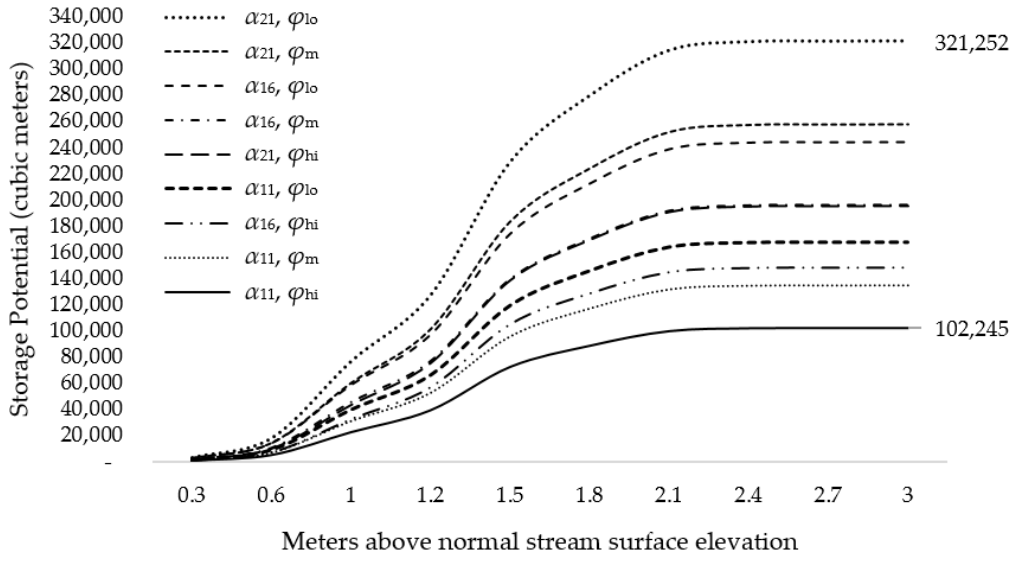


Figure 9. Storage potentials simulated for observed GWAAMON well φhi, φlo, and φm levels, and when the site soils' α value is either 15% (α15), 16% (α16), or 17% (α17) (i.e. a 1% change in α). Storage potentials increase as φ decreases and α increases. The difference between the highest and lowest estimated storage potentials for an entirely inundated study site in this scenario (i.e. when φhi, φlo, and φm are considered and the difference between highest and lowest α is 2%) is 120,636 m3.

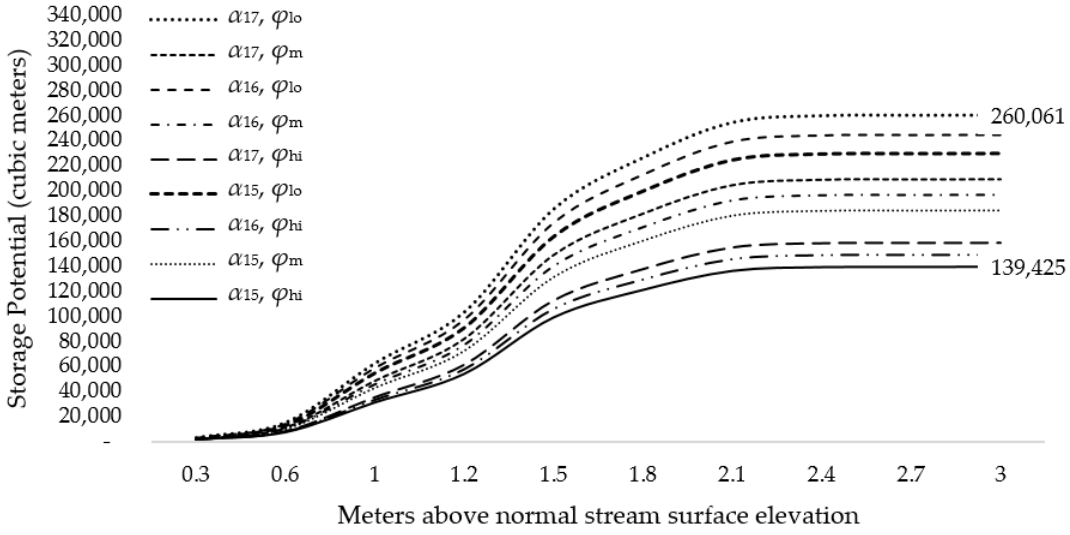


Table 2. Site storage potentials (m3) for eight different conditions: high groundwater table elevation (φhi), low groundwater table elevation (φlo), median groundwater table elevation (φm), available water supply of 11% (α11), available water supply of 15% (α15), available water supply of 16% (α16), available water supply of 17% (α17), and available water supply of 21% (α21). Conditions and respective storage potentials are sorted in ascending order of storability.

	Meters Above Normal									
Storage Condition	***0.3***	***0.6***	***1***	***1.2***	***1.5***	***1.8***	***2.1***	***2.4***	***2.7***	***3***
φ_{hi}, α_{11}	934	5,189	22,643	39,394	72,512	88,667	99,850	102,032	102,173	102,245
φ_{m}, α_{11}	1,366	7,407	31,470	53,076	96,235	117,539	132,191	134,995	135,173	135,260
φ_{hi}, α_{15}	1,273	7,075	30,877	53,719	98,880	120,909	136,159	139,134	139,327	139,425
φ_{hi}, α_{16}	1,358	7,547	32,936	57,300	105,472	128,970	145,236	148,410	148,616	148,720
φ_{hi}, α_{17}	1,443	8,019	34,994	60,881	112,064	137,030	154,313	157,686	157,904	158,015
φ_{lo}, α_{11}	1,798	9,625	40,296	66,758	119,958	146,411	164,533	167,958	168,173	168,275
φ_{m}, α_{15}	1,862	10,100	42,913	72,376	131,229	160,280	180,261	184,084	184,327	184,446
φ_{hi}, α_{21}	1,782	9,906	43,228	75,206	138,432	169,273	190,622	194,788	195,058	195,195
φ_{m}, α_{16}	1,987	10,774	45,774	77,201	139,978	170,966	192,278	196,356	196,616	196,742
φ_{m}, α_{17}	2,111	11,447	48,635	82,026	148,726	181,651	204,296	208,628	208,904	209,038
φ_{lo}, α_{15}	2,452	13,125	54,949	91,034	163,578	199,652	224,363	229,033	229,327	229,466
φ_{lo}, α_{16}	2,615	14,000	58,612	97,103	174,484	212,962	239,320	244,302	244,616	244,764
φ_{m}, α_{21}	2,607	14,140	60,078	101,327	183,721	224,393	252,365	257,717	258,058	258,224
φ_{lo}, α_{17}	2,779	14,875	62,275	103,172	185,389	226,272	254,278	259,571	259,904	260,061
φ_{lo}, α_{21}	3,433	18,375	76,929	127,447	229,010	279,513	314,108	320,647	321,058	321,252

4. Discussion

The results of this natural storage quantification method reflect the degree of uncertainty in attempting to estimate natural water storage potential using a single number, or a single condition. The intent of communicating multiple results in a grid is to illuminate the diversity of storage potentials that exist for inherently dynamic floodplain systems that regularly experience a range of hydrologic conditions, like fluctuating water tables and stream surface elevations. Similarly, the availability and need for water in the West are as mutable as the resource itself, and contemporary water resource planning and policy in this region are starting to reflect that reality. Planning at the local level is key, but cultivating strategies to incorporate alternative methods of water storage at larger scales depends on the development of tools that can be refined for application in a variety of ecosystems, communities, and political climates.

While the methods outlined in this paper were created using Montana-specific data sources, water concerns and water policy structures in the state embody those unique to the region as a whole. The use of a geographic approach and open-source data allowed for the development of a natural storage quantification and site identification system that, while coarse, can be used by a variety of stakeholders and institutions who have access to GIS platforms and interest in exploring the feasibility of natural infrastructure, but not enough time for complex hydrologic inquiries. All of the data types described in this paper are publicly available in similar forms for nearly every Western state where communities eager to contribute to drought and flood mitigation strategies are abundant. The natural storage model framework introduced by this research enables its use by an assortment of organizations and individuals with different concerns and in diverse geographies. This framework leaves room for the consideration of more traditional yet complicated hydrologic parameters, social science, and political contexts. Future research should explore and encourage this process.

To better understand the state-specific implications of model outputs in the Montana case study, results are compared with a traditional storage structure that is being considered in the MSRB. In 2010, construction of the Horse Creek Coulee (HCC) Reservoir was proposed to provide additional water for the residents of four counties within the MSRB. If constructed, the HCC Reservoir would be located about 6 km downstream of this project's natural storage study site. With a surface area of 130 ha and a proposed capacity of 5.5 million m^3, a maximum volume of 691,000 m^3 of contracted water from the Reservoir would be sold and delivered to downstream water users for the period between June 1 and September 30. Construction cost for the Reservoir and HCC dam, not including annual maintenance, is estimated to be over $4 million, or roughly $730 per 1,000 m^3.

With a low groundwater table elevation (φ_{lo}), the fully inundated Melstone natural storage study site has a total site volume (V) of 1,529,700 m^3, or just under one-fourth of the proposed HCC Reservoir's total capacity. When fully inundated with a low groundwater table and high available soil water supply (α_{21}), the study site would be

capable of storing about 50% of the maximum contracted water volume proposed for delivery by the HCC Reservoir, but at one-sixth of the reservoir's volume. When the groundwater table is high (φ_{hi}) and the site is moderately inundated (for example, g_1, or when the stream surface elevation is 1 m above normal), V equals roughly 2% of the HCC reservoir's volume, and with a low available water supply value (α_{11}) the site is estimated to be capable of storing about 3% of the maximum contracted water volume proposed for delivery by the HCC Reservoir. The rate and quantity of recharge from the study site would not be under human control like the delivery of water from the reservoir would be, but it is feasible that a network of distributed storage sites of similar volumes to the one in this study may compare with the storage provided at the proposed HCC site, provided the sites are inundated (though not necessarily simultaneously) by more water during more frequent flood events.

The MSR natural storage model provides a method for quickly identifying sites that are assumed to be more likely to function as natural storage structures, as well as a method for estimating floodplain water storage potential. However, there are several model limitations that must be addressed in order to realize the hydrologic, agricultural, and economic value of potential natural storage sites. No models can perfectly simulate real-world conditions, but models using a great deal of data that are collected regularly (and in the same time frame) using updated measurement techniques, and that are properly validated and calibrated tend to produce more accurate results. Like most models, the success of a GIS-based natural storage model of this kind depends on an abundance of available data. For instance, the model input with the greatest influence on study results was available water storage (α), but the resolution of the SSURGO soil data used in this research should only be acceptable in natural storage modeling estimations for which coarse results are acceptable. For more refined studies, α should be determined using data collected in the field, and stage-discharge rating curves should be established when possible. Further research should also emphasize natural storage model input validation and calibration.

The inclusion of observed groundwater elevations, physical soil characteristics, and high resolution elevation data are integral during storage quantification. Groundwater flux, soil porosity, and surface topography are all fundamental components in hydrologic studies. There is evidence that natural water storage sites contribute to late-season return flows and floodwater attenuation, and identifying locations adequately suited for natural infrastructure as well as their natural storage capacity is important. More well data and *in situ* soil surveys could be used to improve the model accuracy. Nevertheless, research investigating (for instance) the contribution of return flows from natural storage to late-season flows, or the rate of flood attenuation by natural storage sites relies on hydrologic data that vary both spatially *and* temporally. Assuming that groundwater elevations and soil porosities are uniform for a 33 ha study site may only be acceptable for the most preliminary natural infrastructure feasibility studies. Making similar assumptions would be inappropriate for more advanced analyses, but

developing a more reliable and advanced quantification model can be accomplished by a single site visit. More engagement with property owners and water users downstream from potential sites is also critical in evaluating how effectively natural infrastructures can address various water volume needs and water supply concerns. Finally, the assessment of natural storage potential throughout a basin is dependent on the development of hydrologic monitoring projects along tributaries, for which data can be lacking.

Three broad research efforts should be explored to expand upon and refine this work, including 1) improving the accuracy of natural storage potential quantification by incorporating more hydraulic data, local discharge estimates, and analysis of inundation for flood events at the storage areas of interest, 2) identifying the water rights implications related to the implementation of natural infrastructure as an alternative method of water storage, and 3) interviewing stakeholders to determine their specific water needs and concerns, as well as their perceptions of natural infrastructure as a water management tool.

4.1 Improving accuracy in natural storage modeling

Static water storage (*S*) as estimated by the modeling process outlined in this research sufficiently delivers a coarse floodplain water storage quantification method that can be employed inexpensively and relatively quickly in natural infrastructure feasibility assessments. At this stage, this research outlines a method that can estimate a range of water storage potentials, but model calibration targeting input variables is needed to gage model accuracy and error. Additionally, answering important questions regarding storage potential *over time* can be accomplished by incorporating temporally variable data into this framework. Finally, it is essential for researchers making use of this model to comprehend that the various Melstone-specific model input values are least likely to reflect the physical characteristics of other sites. The inputs used in this research are likeliest to generally reflect downstream MSR floodplain conditions, but the MSR is a large and diverse fluvial system with local geomorphologies that are as variable as the system is vast. Because of this, special care should be taken to obtain model inputs specific to research regions and localities of interest to the study at hand.

In general, improving the accuracy of this natural storage model to better understand the contribution of natural storage sites to late-season return flows, for instance, requires the consideration of several other hydrologic variables, including (but not limited to):

- Projecting inundation of floodwater (or diverted water) to the floodplain based on specific flood event discharge and return periods
- Rates of groundwater discharge based on synoptic flow measurements
- Anthropogenic groundwater diversion trends
- Streambed cross sections
- Channel migration patterns

- Local hydraulic conductivity and hydraulic gradient
- Precipitation (rain and snow)
- Surface roughness
- Local geology and lithology
- Stream discharge and stage data directly upstream and downstream of the site
- A vegetation profile of the area, as well as local evapotranspiration rates
- An updated, high-resolution soil survey for more precise physical soil characterization

Analysis and data on each of the variables listed above should be scaled and calibrated according to the specific applications at hand, with an eye for model sensitivity. This is critical since a project exploring seasonal fluctuations in the water storage potential for a distributed network of natural infrastructure sites throughout a watershed calls for different data resolutions than a project probing the daily contribution of outflow from a natural storage site along a single stream reach. In the instance that data for some might not be available online, some of these variables (e.g. surface roughness, stream discharge and stage, stream cross sections) can be collected in a single site visit. Perhaps most importantly, measurements for each new variable in a more advanced natural storage model should be collected with minimal spatial and temporal variability between data sampling conditions in order to maintain the greatest degree of accuracy. In Montana, this can be accomplished, in part, through additional investments in more expansive and automated networks of hydrologic monitoring equipment, including stream gages (already underway), monitoring wells, or climatology stations both along Montana's least-monitored rivers and their tributary systems. In terms of estimating inundation, exiting hydraulic models developed for other purposes may be available for watersheds to predict flood discharge and in turn model inundation using LiDAR data and models such as HEC-RAS.

Moreover, the development of robust natural storage models that meld hydraulic data analyses with geospatial techniques can be expedited through investment in and collaboration with graduate and faculty researchers at Montana's higher education institutions. Through investment in natural resource research in higher education, Montana's state resource management agencies can help generate academic innovation that can produce more management-oriented analyses of services provided by Montana's natural resources.

4.2 Water rights implications of natural infrastructure

For states in the western U.S., the Prior Appropriation Doctrine governs when, how, for what purpose, and how much water may be allocated, diverted, distributed, and put to use. Historically, water use was considered most efficient when every last drop was diverted from a river and used before it could reach the sea, but a shift toward valuing 'water for the environment' has complicated a doctrine whose history is rooted

in valuing industrial and agricultural innovation over conservation. Water for the environment is legally a relatively new concept in western water rights structure. Instream flow rights are common throughout the West, and in many states (like Montana) a seamless process for reserving water specifically for natural infrastructure could prevent future conflict, but it has yet to be established. For example, water users in the MSRB have expressed concern about the possible disputes arising from the impacts of natural infrastructure on the water rights of water users downstream from Fort Peck. The high flow velocities resulting from and contributing to stream incisement lead to lower residence time of water in the MSRB. While slowing water down in the MSRB would be beneficial for water users diverting directly from the MSR, issues may arise if users downstream of Fort Peck notice a sudden drop in their supply that may be traced to management changes in the MSRB.

In addition, a site that intermittently provides storage through the slow release of early spring runoff may provide a meaningful service to downstream water right holders whose supplies tend to dwindle in the late summer. Junior and senior irrigators alike may also value and support the implementation of natural infrastructures or the enhancement of natural storage sites for their capacity to attenuate potentially devastating volumes of floodwater during large but infrequent flood events.

Another form of natural storage might involve incentivizing irrigators to partially convert their operation from center pivot or sprinkler back to flood irrigation. Because such a conversion would normally pose an economic disadvantage for the individual irrigator due to lower crop production and higher labor costs, the potential financial loss would have to be offset through annual financial compensation (e.g. tax credit) or perhaps a conservation easement. These issues are important to consider as the state of Montana continues to identify the adverse impacts on water rights that may arise from various types of natural infrastructures, and explore strategies that might best curtail those negative consequences in legally water deficient basins. Questions regarding the potential impact that natural infrastructure may have on legal water agreements should be investigated with a range of stakeholders (e.g. tribes, farmers, ranchers, municipalities, FWP, conservation districts, industry, or canal managers).

4.3 Interviewing stakeholders

Further research should determine more explicitly how natural infrastructures could provide meaningful storage services to different water users, and would require an understanding of the unique water needs affected stakeholders have before the value of a natural storage service can be assessed. For instance, a senior water right holder whose property was destroyed following a 100-year flood event likely has different concerns related to water than a more junior water right holder in the same basin whose property does not experience substantial flood damage, but whose water right is regularly "called on" and relinquished to senior water users. Both water users in this example may live in the same basin, or even reside near the same town, but there is

significant contrast in the types of natural water storage services needed to address their concerns. The senior water right holder is less likely to have their water called, but because of their risk to flood damage, they would likely benefit more from the implementation of natural infrastructures that promote the attenuation of large volumes of floodwater from events that may only occur once every 50 years. Alternatively, the junior water right holder may prefer the implementation of natural infrastructures that promote the more regular seasonal capture and storage of smaller early spring runoff volumes that are slowly re-released in the form of late summer return flows.

Moving forward with natural infrastructure projects after considering the unique and varying needs of the affected stakeholders can maximize the probability that the project likely to offer the most meaningful service is developed. Watershed coalitions and advocacy groups are expediting this process for government agencies in the West by collectively identifying prospective project locations that have the greatest social value. In the MSRB, the MWC contributed to the development of the Musselshell Watershed Plan, a report which summarizes a number of high priority water planning projects intended to assist the MWC in its continued development and implementation of stakeholder-driven water management efforts in the basin [46]. This plan was also designed to continue the MWC's work to encourage collaboration among landowners, water user associations, conservation districts, counties, municipalities, and state and federal agencies, all of whom assisted in identifying potential management strategies and projects. Beyond mitigating flood risk and water shortage, projects of interest include salinity, total maximum daily load, and cottonwood monitoring, fisheries enhancement, canal and bridge repair, and weed management. This plan facilitates the identification of the most pressing basin-wide water planning projects (including this natural storage model) for MSRB water users as a collective whole. Assessing the feasibility of natural infrastructure implementation, however, can still benefit from collaborating with individual landowners to better understand how their specific and varying needs might best be addressed.

The implementation of natural infrastructure in a place like the MSRB would likely begin with a limited number of carefully selected sites and consultation with only the most affected downstream water users, including irrigators and other water right holders, and water resource managers from various institutions. Failure to consult with relevant stakeholders before the enhancement of natural storage sites could result in the development of projects that do not address their concerns. For example, investment in natural infrastructure sites better suited to provide services related to the attenuation of floodwater may be of greater interest and met with more support by water users in the Lower MSRB where the impacts of large flood events has tended to be more severe than in the Upper MSRB. Similarly, dismissing landowner involvement in the planning process could result in the implementation of natural infrastructures in areas where concerns for water shortage are less severe, for example places that are removed from the main stem of the MSR where dominant farming or ranching practices do not rely on

irrigation, or where agricultural development is effectively non-existent. Finally, it is improbable that the existence of a few wetlands or floodplains that are enhanced by natural infrastructures would be capable of helping meet all of the varying basin-wide water demands. For this reason, a distributed, watershed-scale network of enhanced natural storage sites tailored to the needs of local water users may be necessary for a significant storage service to be realized for the greatest number of people.

The application of projects like these hinge on the support of the communities where they'll be implemented. Research on the social dimensions of natural infrastructure is required to assess community perceptions of water use, water availability, and management practices. Although this paper is concerned primarily with the physical aspects of natural water storage, future research on the successful implementation of natural infrastructures as alternatives or additions to traditional water capture and retention systems (e.g. dams, canals, wells, ditches, etc.) should consider the broader legal, social, political, and economic contexts that shape water scarcity and uneven availability of water among different social groups.

5. Conclusions

Mounting concerns over the impacts of climate change on water resources in the West are incentivizing state agencies to explore alternative water shortage and flood mitigation strategies. Montana state agencies responsible for monitoring and ensuring adequate water supplies and quality for the benefit of people and the environment are exploring methods of increasing water availability through the protection and enhancement of natural processes and landscapes.

Natural storage processes, like the services provided by wetlands and floodplains, act to not only slow down water and raise the streambeds in incised and entrenched streams, but have also been shown to effectively attenuate and reduce high peak runoff during large flood events. In the MSRB, the capacity of natural storage and natural infrastructures to address both water shortage and the unprecedented size of recent flood events have caught the attention of a variety of water users from irrigators to fishery managers. The MSRB was selected as a broader study region due to the degree of collective participation and expressed interest from the MWC and other MSRB residents to reduce their vulnerability to water shortages and extreme flood events by collaborating with state agencies and academic institutions, and by exploring more environmentally integrated methods of natural water storage.

In addressing one of the short term natural storage recommendations listed in the DNRC's MSWP, this research produced a cost- and time-effective GIS-based method of estimating the water storage potential of a portion of MSRB floodplain, and for identifying potentially viable natural storage sites using open source data. This model is intended to be used and customized by other state agencies interested in exploring the feasibility of natural water storage in the West. A distributed network of multiple study sites of similar size to the one analyzed in this paper may be able to match water

volumes contracted for delivery by a proposed reservoir downstream of the study site. Still, further research and the addition of other hydrologic variables in this model, as well as model calibration should be considered if a robust framework for assessing the temporal influence of natural storage sites on water supply is to be developed. In addition to the inclusion of hydrologic data within the natural storage model, identifying the implications of natural infrastructure on water rights, and understanding stakeholder water needs, concerns, and landowner perceptions of natural storage would be useful in expanding the applicability of this site identification and storage quantification model to natural infrastructure planning and water management efforts throughout the western United States, and beyond.

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Abbreviations

The following abbreviations are used in this manuscript:

DEM: Digital Elevation Model
DNRC: Department of Natural Resources and Conservation
DOR: Department of Revenue
FLU: Final Land Unit
GIS: Geographic Information Science
GWAAMON: Ground Water Assessment and Monitoring Program
GWAP: Ground Water Assessment Program
HCC: Horse Creek Coulee
LiDAR: Light Detection and Ranging
MBMG: Montana Bureau of Mines and Geology
MSR: Musselshell River
MSRB: Musselshell River Basin
MSWP: Montana State Water Plan
MWC: Musselshell Watershed Coalition
NAIP: National Agricultural Imagery Program
NRCS: Natural Resources Conservation Service
RATT: River Assessment Triage Team

SSURGO: Soil Survey Geographic Database
STATSGO: State Soil Geographic Database
SWL: Static Water Level
USGS: United States Geological Survey

Appendix A

This inundation model was originally created by Tony Thatcher at DTM Consulting, Inc., based in Bozeman, Montana, and relied on LiDAR bare-earth imagery provided to the author at no cost by Mr. Thatcher, and Ms. Karin Boyd of Applied Geomorphology, Inc., also in Bozeman. Analysis was completed using ArcGIS 10.2.

1. Create a new Polyline dataset and edit.
2. Draw cross sections across area of interest (from one floodplain edge to the other), keeping the same direction for all cross section lines. Make sure that the lines stay inside the elevation dataset coverage, and that lines run perpendicular to the main channel and valley trend.
3. Add a XS_ID field and populate it with sequential integer values.
4. Create a Bounding Box dataset and edit.
5. Create a bounding box for the resulting inundation surface. This should be 100% inside the elevation dataset coverage.
6. Create a polygon dataset that defines the area of the corridor where you want the *z* values for each cross section.
7. Clip the Cross Sections with the Minimum *z* area polygon.
8. Open the Interpolate Shape tool and process the clipped cross sections using the elevation dataset.
9. Open the Attribute Table, add a Min_Z field, and then use the Calculate Geometry > Minimum Z of Feature to populate it with the minimum elevation value for each clipped line.
10. Export the Attribute Table.
11. Join the exported table to the Cross Sections Attribute Table using the XS_ID field.
12. Add a new Min_Z field and calculate the value from the joined table.
13. Remove the join.
14. Create a TIN using the Min_Z field (H2O_Surf).
15. Use the TIN to Raster tool to convert the TIN to Raster (H2O_Surface).
16. Use Raster Calculator to calculate the difference between the DEM and the H2O_Surface (DEM – H2O_Surface).

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CHAPTER 4

CONCLUSION

Water users in Montana have shown increasing concern over the impacts resulting from climate change-induced water shortage and extreme flooding. The 2015 release of the DNRC's MSWP reflects the existence of these concerns at institutional levels. Nearly half of Montanans live in drought areas, and balancing competing demands for new sources of water are complicated by ongoing water rights adjudication, rapid population growth, and widespread conversion to more efficient agricultural irrigation methods.

Several of Montana's natural resource management agencies and private organizations are promoting the services provided by natural floodplains and wetlands as alternatives to traditional water storage methods. Evidence of the adverse impacts associated with traditional storage structures contrast with studies showing that natural water storage features and infrastructures can be effective tools for encouraging water retention during episodes of water shortage and flood. The hydrologic services provided by flood irrigation have also been shown to mimic and enhance those provided by wetlands. Research on natural infrastructure implementation emphasizes the need for a shift in the way water storage is traditionally conceptualized as a series of surface reservoirs toward viewing it as a process that addresses the needs of multiple stakeholders. While a major paradigm shift is unlikely, the use of natural infrastructures as a means of mitigating water shortage and flood risk continue to gain interest in Montana. The MSRB was selected as a broader study region due to the magnitude of

extreme MSR flooding in recent years, the shortage of water resulting from stream incision throughout the MSR, and the basin-wide cooperation among MSRB residents toward improving their watershed using nontraditional methods.

The DNRC has listed the need for a pilot project quantifying the storage capacity of potential natural storage sites as a short term recommendation for implementing natural infrastructures. Though other studies have provided a framework for calculating the storage potential of floodplains and wetlands, the development of a method for identifying potential sites and quantifying their natural storage potential in a timely and cost-effective manner that can be used by water managers has yet to be established. The research outlined in this paper addressed this managerial need through the development of a geospatial method for identifying possible natural storage sites, as well as estimating their water storage potential. Storage potential in this study was defined as the volume of water capable of being stored in the ground between the surface of a potential study site and the groundwater table under field capacity conditions.

Hydrologic processes contributing to the flux of water in and out of a study site were not considered. In the instance that this model is refined for more precise application in research probing the influence of natural storage on hydrologic processes (i.e. return flow, streamflow, or groundwater aquifer recharge), it is recommended that additional hydraulic parameters be considered. Model results support the need for a distributed network of natural storage sites throughout the MSRB in order for a meaningful storage service to be provided to the greatest number of residents. The identification of potential sites in such a network can be facilitated by greater

hydrologic data collection along MSR tributaries in the upper and lower basin. In addition to the inclusion of more hydrologic data within the natural storage model, identifying the implications of natural infrastructure on water rights, and understanding stakeholder water needs, concerns, and landowner perceptions of natural storage would be useful in expanding the applicability of this site identification and storage quantification model to natural infrastructure planning and water management efforts throughout the MSRB, and perhaps the rest of Montana.

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