Managing Active Forestry Lands for Increased Water Retention:

a New Approach for Protecting Summer Water Supplies

in the Western United States

by

Daron Williams

A Thesis
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2016

This Thesis for the Master of Environmental Studies Degree

by

Daron Williams

has been approved for

The Evergreen State College

by

____

Kevin Francis, Ph. D.
Member of the Faculty

____

Date

ABSTRACT

Managing Active Forestry Lands for Increased Water Retention:
a New Approach for Protecting Summer Water Supplies
in the Western United States

Daron Williams

The Western United States is reliant on mountain snowpack for its water supply in the hot dry summer months. Climate change combined with human driven land-use change is changing the volume and the timing of this snowpack – resulting in increased droughts and water stress across the region. On either a low emissions track or a high emissions track the impacts of climate change will become worse overtime resulting in water mangers no longer being able to ensure adequate water supplies for the communities that they serve. Current methods for addressing this problem rely on conservation efforts and building new infrastructure such as canals, dams and other water storage structures to decrease demand and increase supply of water. These methods are likely to not be adequate for addressing the full impacts of climate change.

This thesis outlines method through the use of a pilot study to use working lands – specifically forestry lands – as a way to increase water retention throughout the watersheds of the Western United States. Specifically, this pilot study looked to answer the question: can bioswales be implemented within clear-cut sites to effectively retain water? The results of the pilot study showed that under specific soil conditions soil moisture levels can be significantly increased even in the face of serve drought by implementing bioswales within clear-cut lands. While this method is not applicable to all working lands it shows the potential for implementing similar methods with the shared feature of increasing water retention to increase soil moisture levels and help protect summer water supplies in the Western United States.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I want to thank my reader Kevin Francis for his help and wisdom throughout the process of completing this thesis. I also want to thank my research advisors Erin Martin and Paul Pickett for helping me with my experimental design and planning out my field study. Also, a big thank you to the University of Washington Pack Forest for allowing me to setup my field study within their experimental forest and for providing advice and aid in setting up the field study.

Finally, I want to give a big thank you to my friends and my family. Especially my parents who helped install all the field equipment and of course to my amazing wife Michaela – I could not have completed this thesis without her ongoing support both at home and at the field site. Michaela's support, wisdom and advice throughout the process was what made this possible – Thank you!

Introduction

The Western United States, arguably, is built on water. While every human community is reliant on water, no other region within the United States has built as complex of a water system or is as reliant on that system. The Western United States relies on vast water systems such as the Colorado River System and the Columbia River System. Due to the region's lack of natural water sources, these water systems were necessary for the type of development that has been seen in the region. These water systems work by trapping and storing the spring snowmelt from the region's mountain ranges that naturally feed the rivers that make up the core of these water systems. The spring snowmelt and other sources of runoff can be thought of as the natural base flow of water through these water systems. Capturing the natural base flow of water through the region results in an increase in usable base flow, i.e. the amount of natural base flow available for human use. Today the region is facing a new challenge due to climate change which is changing the volume and timing of the natural base flow within the region. Population has also seen a steady increase in the region which is exacerbating the impact of climate change by increasing the amount of water needed at the same time that the supply of water is being negatively impacted.

Historically, the increase in demand due to population growth has been managed by reducing per capita consumption through conservation efforts. This has resulted in total water demand holding steady within the region despite the increase in population. With the threats of climate change and continued increases in population it seems unlikely that the region will be able to meet future water demand without a combination of conservation and new water sources. Conservation efforts focus on reducing per capita use of water by directly reducing the amount of withdrawals from usable base flow. This approach reduces the amount of natural base flow that needs to be harnessed as useable base flow but does not impact the timing or the volume of the natural base flow. The other approach that has traditionally been used is to supplement existing sources with new sources of water. This approach works by increasing the total amount of natural base flow flowing into a water system which also increases the amount of useable base flow available for meeting water demand. It should be noted that finding new water sources without negatively impacting the environment is becoming a daunting challenge (Anderson & Woosley, Jr., 2005). With the increase in the number and severity of droughts caused by climate change and the shift of the timing of spring snowmelt earlier in the year this challenge will become even harder to meet than it is today. In order to meet these challenges and due to the limitations of conservation efforts and the difficulties associated with finding new water sources water managers need a new approach to ensure adequate water supply for the communities of the Western United States.

Currently the impact of land use on water supply within the Western United States has been understudied outside of the impact of urban environments on storm water runoff (Defries & Enshleman, 2004). While it seems likely that the conversion of natural ecosystems to human use for forestry products, agriculture and other uses would have an impact on the flow of water through these areas the cumulative impact has not been determined in the existing literature. A few studies have been done showing changes in base flow caused by land use change within small watersheds but the results of these studies have yet to be scaled up beyond these small watersheds. The first of these paired watershed studies was done at Wagon Wheel Gap in 1928. This study looked at the impact of clear-cutting a forest on stream flow (Bates & Henry, 1928). Modern studies have continued and expanded this research. These studies are covered later in the literature review section of this thesis.

Given the likelihood that human land use is negatively impacting base flow within the Western United States this thesis examines the possibility of using specific land management techniques within working lands[1] to counter these impacts. Even if land use practices are not having a negative impact on the water systems within the Western United States it is likely that these lands could be managed in a manner that would optimize water retention and result in an increase in usable base flow. This could be achieved by increasing water retention on the working lands which would increase the transfer of surface water to groundwater. This would potentially result in a shift in the timing of when spring snowmelt pulses reached large established water systems to later in the year. Doing so would directly counter one of the major impacts of climate change in the Western United States and would have the potential to increase the useable base flow.

Large-scale research projects will be needed to explore the possibility of managing working lands to optimize water retention. Given the urgency of finding new sources of water for the Western United States it seems prudent to start exploring this new management approach in order to provide guidance for developing larger projects. For the purposes of this thesis, I'm conducting a pilot study that will look at a specific

[1] Working lands includes those lands associated with agriculture, forestry and other production/extractive based uses.

method within a specific type of working land. This pilot study was implemented within the University of Washington Pack Forest in a clearcut area. The pilot study involves the testing of the use of bioswales to increase water retention within the clearcut area in order to answer the following question: Can bioswales be implemented within clearcut sites to effectively retain water?

To answer this question two experimental plots along with two control plots were established. The experimental plots each contain three bioswales. These bioswales and the control plots were wired with soil moisture sensors and data loggers to measure changes in soil moisture level in order to conduct a comparative analysis. This study tracked soil moisture levels from May 2015 through December 2015. This time period allowed for capturing of data covering the transition from wet conditions in spring, to dry conditions in summer and back to wet conditions in the following fall and winter.

In this thesis I will start by going through the existing literature to show how water has been traditionally managed within the Western United States, the impacts of climate change and forestry practices, how bioswales have traditionally been used and a survey of existing methods for increasing water retention within rural sites. From this literature review I will cover the methodology that I used to conduct this study, the analysis of the collected data and the results of this analysis. I will conclude with a discussion on the practicality of using bioswales to increase water retention within clearcuts. I will also discuss possible future research and the need for policy changes to better manage working lands for water retention.

The approach argued for in this thesis would represent a major adjustment to the way that water resources are managed within the Western United States. While my pilot study will only focus on one small field site, implementing this type of land use practice on a scale that would make a noticeable difference would likely require a large percentage of existing working lands and lands brought into production in the future to be managed using these practices. This would require new regulations, policies, financial incentives and a full engagement of local communities to ensure that these practices could be implemented successfully. A change of this magnitude requires a clear understanding of where we are currently, a sense of urgency to justify why we need to change, and a sense of practicality to the proposed changes. In the following literature review section of this thesis I will seek to fully explore each of these requirements to make the case for why this new direction is urgently needed and can be practically implemented.

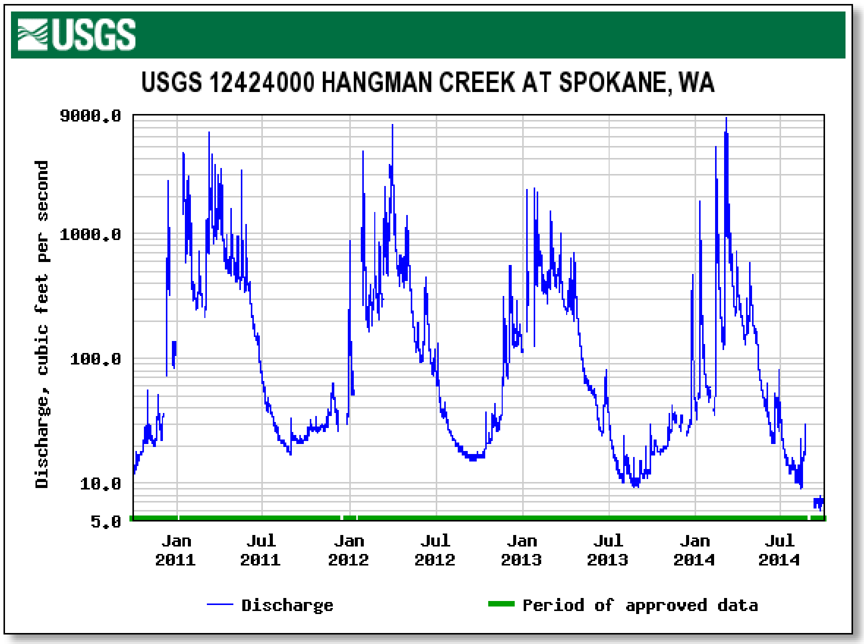
Literature Review

Water resources managers are facing an ever-growing challenge of how to meet the increasing demands for water in the face of changes in the timing and amount of precipitation due to climate change and human land use practices. The Western United States, with its relatively wet winters and dry summers, is dependent on a specific pattern of precipitation to ensure adequate water supply. This pattern is based on the accumulation of snowpack in the mountains of the region and the slow melting of the snowpack in the springtime through early summer. The Western United States relies on a complex set of water systems built around larger rivers such as the Colorado and Columbia to harness and trap the natural base flow to increase the amount of usable base flow available for the regions hot and dry summers. However, today that pattern has changed and the base flow generated by spring snowmelt is no longer occurring when expected or in the necessary amounts to supply the region with adequate water. But before we can determine how to address this problem we must more fully understand the current water system and why it is struggling to meet the impacts of climate change and human land use practices.

Historical Overview of Human Water Use – Storing the Base Flow

The development of Western North America by the United States was made possible through the use of dams and other water management infrastructures such as canals. This allowed for water to be moved from where it was to where it was needed. The largest such example of this type of development is the Colorado River System which provides water for cities, farms and other human uses through the South Western United States (Fradkin, 1981) (Anderson & Woosley, Jr., 2005). Essentially, this approach to water management involved focusing on the largest rivers such as the Colorado and Columbia and then constructing large dams at key points along these rivers to trap and store the water flowing through the rivers. Due to the climate of the Western United States the majority of the water would flow through the watersheds to these major rivers during the spring months with flows being greatly reduced during the summer months (figure 1).

Figure 1: Example of a spring snowmelt driven system with spikes likely caused by land use practices



This pattern of natural water flow through the watershed can be thought of as the base flow for the system. Dams and canals captures and redistribute this base flow from reservoirs to communities throughout the Western United States in order to ensure adequate water supply during summer months when it is most needed by cities and farms (Billington, Jackson, & Melosi, 2005). This use of dams and canals interrupts and captures the base flow but does not result in an increase in the total volume of the base flow. Instead it simply changes where the base flow travels, in what quantity, and when it travels. But not the total amount available for human consumption. This lack of change to the total volume of water contained in the base flow has become a major weakness in this system in the face of climate change. I will address this in a later section on climate change within this literature review.

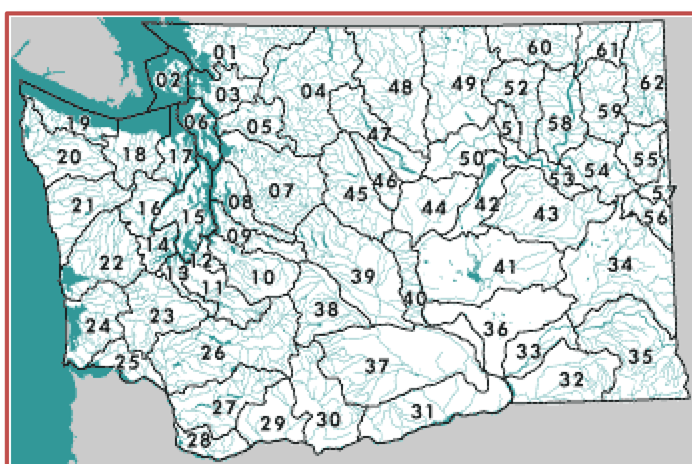
Historically this use of dams was seen as enhancing the existing water cycle and was so successful at harnessing water for the development of the Western United States by

American settlers that nearly every major river has been dammed (Consensus Building Institute, 2012). With the damming or the region’s rivers it has been generally accepted that the era of big dams is largely over and that a return to the construction of large dams is unlikely (Billington, Jackson, & Melosi, 2005). It should be noted that in response to droughts and water shortages in recent years, Washington State and California have proposed and in some cases successfully implemented projects to enlarge existing dams to increase water storage capacity (US BLM, WA DOE, 2012) (San Diego County Water Authority, 2015).

The dam enlargement projects in the Yakima area of Washington State and the San Diego area of California could indicate that while new large dams are unlikely in the face of droughts and water scarcity there could be a push to enlarge existing dams. While base flow from the Colorado River no longer reaches its mouth most years many other rivers such as the Columbia River do. Despite the negative environmental consequences enlarging dams could have in the face of climate change and water shortages it will be very tempting to do so in order to retain more of the base flow. In addition to the enlargement of dams, there have been recent efforts to expand existing canal systems in order to move water from sources that are still plentiful to areas of declining water supply (Fort & Nelson, 2012). An example is the ongoing efforts to build a new canal system from Lake Roosevelt (Columbia River) to areas in Central Washington located south of I-90 in order to replace rapidly depleting ground water sources for the area’s farmers (Department of Ecology, 2014). These recent developments indicate that despite the claims that the era of big dams is over, water resource managers appear to be unwilling or unable to respond to the challenges of climate change and land use practices with new techniques.

Conservation efforts have been implemented successfully in the face of droughts. However, conservation efforts, like the use of dams, do not change the base flow of water through a watershed. This means that conservation efforts are only effective if they result in decreasing demand to a point lower than or equal to the base flows made available for human use by existing water supply infrastructure such as dams and the reservoirs they create. With rising human populations, continued impacts of human land use practices, and changes to the timing and quantity of the base flows due to climate change it seems unlikely that conservation efforts alone would be able to ensure adequate water supply for human needs (Anderson & Woosley, Jr., 2005). Also, it is likely that many dams cannot be enlarged due to geological limitations and the negative impacts such enlargements could cause to the surrounding land and downstream environments. When combined with the lack of locations for new dams and the limitations of conservation efforts it seems likely that water resource managers will need a new approach in order to meet future water demand. Overtime there has been a call for a new approach to meeting water demand through alternative methods – particularly from a school of thought commonly referred to as integrated watershed management.

Figure 2: Water Resource Inventory Areas - Washington State Department of Ecology



Integrated watershed management is an approach to watershed management that calls for water resources to be managed on a watershed level (Heathcote, 2009). This requires water resources be managed across an entire watershed instead of focusing at the end user (conservation and consumption) or at the point of storage (dams/reservoirs and wells/aquifers). An example of this type of approach is the water resource inventory areas (WRIAs) in Washington State (figure 2). It should be noted that WRIAs don't match watershed boundaries exactly and cross some traditional political boundaries such as county boundaries but do not cross state or country boundaries – Watersheds cross all traditional political boundaries. Despite the success of the use of WRIAs and other integrated watershed management policies this approach has struggled to replace the traditional approaches to watershed management (Blomquist & Schlager, 2005). Traditional approaches fit within existing political frameworks while an integrated approach has required breaking down traditional political frameworks and focusing on a smaller local level as defined by the watershed boundaries. Despite the current limitations in the implementation of this approach to watershed management this thesis looks at one possible tool for use within an integrated watershed management policy approach. With the challenges of climate change and the limitations of existing water management strategies it is likely that elements of the integrated watershed approach will be used.

Forestry Practices and Hydrology – Changing the Base Flow

As covered in the previous section the current techniques used for managing water resources have relied on storing base flow but not fundamentally attempting to increase or decrease the base flow. Land use practices implemented by other resource managers and society in general have had an impact on the base flow. Forestry and agricultural practices in addition to urban development are examples of practices that have impacted the base flow of the watersheds within the Western United States. In this section, I will be focusing on forestry practices and more specifically the act of clear-cutting. Within the Western United States forestry practices have the potential to have a dramatic impact on the base flow. For example, 52.6% of the land in Washington State is classified as forestry land (Campbell, W addell, Gray, Andrew, & tech. eds., 2010). By analyzing the impacts of clear-cutting and forestry practices on base flow within a watershed we can paint a picture of how these practices impact the effectiveness of existing water infrastructure within the Western United States. Due to the reliance of the Western United States on the timing of spring snowmelt and the amount of water available for use in the summer months, the impact of forestry practices will be analyzed through the lens of these two characteristics in the following two subsections.

Minimum Water Flows

The removal of trees from a forest through clear-cutting decreases the rate of transpiration (the return of water back to the atmosphere by plants such as trees) and interception (the capture of water by plants for use in their biological processes) of water flows. This decrease in interception and the resulting decrease in transpiration results in an overall increase of minimum water flows within the streams of a watershed (Scott & Lesch, 1997) (McGuinness & Harrold, 1971). This research shows that the amount of water being intercepted by trees within a forested watershed actively prevents a significant amount of water from traveling through the watershed. This means that tree coverage may decrease the minimum flows within a watershed, which from the perspective of water managers could be a negative impact. When forest cover is removed the research indicates that the decrease in interception increases minimum flows within the watershed. This increase in minimum flow becomes meaningful once approximately 25% of a watershed has been logged, with minimum flows decreasing as vegetation cover returns to the logged area due to increasing interception by the returning vegetation (Johnson, 1998). It should be noted that the research done by Johnson was conducted within temperate European forests and may not be applicable to all forests within the Western United States. In addition, research conducted within the coastal forests of the Pacific Northwest has indicated that the coastal forests show an overall decline in minimum water flows due to reduced moisture from fog drip i.e. moisture condensing on forest plants from fog and falling to the ground (Andreassia, 2004) (Ingwersen, 1985). However, this research is likely not applicable to the drier interior watersheds that make up much of the Western United States. It should also be noted that adequate water supply is most vital during hot drier summer months when minimum streamflow is reached within snowpack driven systems in the Western United States. An increase in minimum flows during these summer months would imply an overall increase in what could be considered the usable base flows within a watershed from a water manager's perspective.

While the research shown here can be used to argue that from a water management perspective clear-cutting would be beneficial by increasing the usable base flow, these practices come with well understood negative environmental impacts. In addition, research conducted by the US Forest Service indicates that the forests within Washington State will see an increase in water stress by almost 30% by 2040 (Littell, et al., 2010). Finally, during conversations with local foresters I was told that clear-cutting used to be defended as having a positive impact on water supplies. However, this view point has not been considered as valid since the 50’s or 60’s (informal interview). Clear-cutting practices are likely to increase the water stress by increasing sun exposure and decreasing the amount of water retained within the watershed. This would likely compound the impact of climate change on these forested watersheds by further increasing fire risk. Since forestry lands are not irrigated as farmlands often are, removing water from these lands seems likely to have substantial negative impacts. Based on this it seems clear that clear-cutting should not be used as a method for increasing the base flow.

In addition to the direct impacts of clear-cutting a recent study conducted within Washington State has shown that the average age of the trees within a forest has a major impact on streamflow. The study found that actively growing forests can transpire upwards of three times the amount of water as an old growth forest (Mckane, et al., 2015). This study found that this had a significant impact on streamflow. The focus of this study was on improving summer streamflow for salmon recovery efforts but it would also benefit human needs for water supply.

Timing of Spring Snowmelt

The Western United States is dependent on spring snowmelt from mountain forests within the region to provide the base flow that is harnessed by dams and other water management infrastructure for human land use practices (Stewart, Cayan, & Dettinger, 2004). If the timing of snowmelt changes in response to clear-cutting and other forestry practices, then this could have a negative impact on the amount of base flow available during the summer months. This potential impact was first studied as part of the first paired watershed study which was conducted at Wagon Wheel Gap in Colorado.

This study showed that clear-cutting resulted in the spring snowmelt shifting earlier in the year by an average of 12 days (Bates & Henry, 1928). Contemporary paired watershed studies done in the Fool Creek watershed within the Fraser Experimental Forest have indicated that spring snowmelt shifted by an average of 7.5 days earlier in the year in response to clear-cutting practices (Troendle & King, 1985). The researchers indicated that this shift was likely caused by an increase in the amount of sunlight reaching the snowpack, which then caused an increase in the rate of melting. Based on these studies, it is likely that clear-cutting is contributing to the shift in the timing of the snowmelt. This likely results in a larger amount of the base flow reaching lower watersheds and their corresponding water storage infrastructure earlier in the year. While this water could be stored it would be subject to higher levels of evaporation due to the increased time that it would need to be stored, and the amount of base flow able to be stored by the dams might decrease if a greater percentage of the base flow reached the dams earlier and in a shorter window of time.

Overview and Conclusions on the Impacts of Forestry Practices on Base Flow

The research outlined in the previous two subsections show that the removal of trees from a forested area through clear-cutting is likely to increase minimum water flows and shift the timing of the spring snowmelt earlier in the year by 7.5 to 12 days. As noted earlier research into the impact of clear-cutting on streamflow has been limited. This has largely been due to the lack of focus on quantifying the impacts of land use practices and streamflow (Defries & Enshleman, 2004). However, current research into these impacts has been conducted within small watersheds and the cumulative impact of clear-cutting across multiple watersheds on lower watersheds has not been studied. This lack of research has been highlighted as a major gap that needs to be addressed due to the assumed but currently unquantified impacts of land use practices on the hydrological cycle and corresponding base flow (Defries & Enshleman, 2004).

Despite this lack of research, it will be assumed moving forward for this pilot study that these impacts do scale up beyond small scale watershed processes and that when combined with other land use practices, such as those associated with farming, that there is a measurable impact on the base flow within impacted watersheds. It seems unlikely that there has not been a measureable impact on the base flow within these watersheds as they have been converted from natural ecosystems to largely consisting of manmade systems such as timberlands, farmlands and urban lands. Finally, if the impacts of forestry practices do not scale it may still be possible to actively manage forestry lands and other working lands to enhance the base flow.

Climate Change and Hydrology – Changing the Base Flow

Water managers in the Western United States have focused on capturing and transferring the base flow of water through the use of dams and other infrastructure. While this has resulted in water being made available to cities and farms that are not located near large water bodies, it has not increased the total volume of the base flow. In addition, clear-cutting and other forestry practices have directly impacted the base flow of these systems. While more research is needed, it is likely that these practices have a negative impact on usable base flow. The cumulative impact of clear-cutting and other land use practices on the base flow of water available in watershed has been understudied and has potentially resulted in a vulnerable situation that is susceptible to shocks from droughts and other disruptions in water supply (Defries & Enshleman, 2004).

Unfortunately these water systems are now facing a major shock in the form of climate change (Cook, Ault, & Smerdon, 2015).

Climate change is impacting the timing of the spring snowmelt, which has caused rivers across the Western United States to reach peak flow earlier in the year. Research that looked at the Western United States found that climate change has resulted in the temporal centroid of streamflow (the point in time where half of the total water that will move through a stream or river has already moved through it – i.e. half of the base flow) to shift 30 to 40 days earlier in the year within heavily impacted areas, which cover much of the Pacific Northwest, Sierra Nevada and Rocky Mountains (Stewart, Cayan, & Dettinger, 2004). The shifting in the timing of the flow through rivers and streams is predicted to get worse if climate change continues unabated (Georgakakos, et al., 2014).

In addition to the changes in the timing of the flow of water through the Western United States, climate change is also changing the amount and timing of precipitation and increasing temperatures (Field, et al., 2014). Droughts such as the one that impacted the Western United States from 2014 through 2015, which was historically unprecedented, are likely to become the norm (Griffen & Anchukaitis, 2014) (Cook, Ault, & Smerdon, 2015). The 2015 drought forced California to implement drastic water conservation programs, resulting in some farmers choosing to leave their fields fallow and has had a major impact on the livelihood of communities across the state (Marcum & Gauthier, 2015).

Given the challenges that California water managers have faced with addressing the current droughts, if these droughts become the new normal it seems unlikely that the current water systems can handle this without new management policies and techniques. The initial response to these shocks will likely be done through conservation efforts as California has already done. While effective in the short run these efforts have no impact on the base flow and only impact the demand placed on the water system. With climate change reducing the available base flow and this being further impacted by land use practices it seems likely that conservation efforts alone will not be enough to ensure adequate water supply. In addition, the traditional methods for managing water through the use of dams and other infrastructure does not result in an increase in the total volume of water making up the base flow within a water system. Since conservation efforts and traditional water management efforts are unlikely to be able to address the shocks caused by climate change and land use practices it seems clear that a new set of tools for meeting future water demand will be needed. These new tools will need to be capable of directly increasing the available base flow of water throughout the water systems of the Western United States.

Modifying Forestry Practices – Pilot Study for a New Direction

As I outlined earlier in this paper climate change and land use practices such as clear-cutting are resulting in the timing of the spring snowmelt shifting earlier in the year. While other land use practices associated with working lands are also impacting the base flow of water it is beyond the scope of this paper to analyze all of the various land use practices. This section is focused on showing the feasibility for water resource managers to implement a specific solution to the impacts of clear-cutting on base flows. Due to this focus the potential solutions to climate change such as reducing greenhouse gas emissions will not be discussed due to the assumption that water resource managers have little direct say over the implementation of policies that could combat climate change. In addition, it will be assumed that even if climate change is addressed that an increase of 1.5 to 2.0°C is likely – this would still result in a significant impact to the available base flow across the Western United States.

Adopting an Urban Solution to Address the Impacts of Clearcuts – Bioswales

There are likely many possible methods for addressing the impact of clear-cutting and other forestry practices on base flows. As outlined earlier, clearcuts result in spring snowmelt and the corresponding peak in water flow to shift earlier in the year. Any method that could be implemented within clearcuts that increases the travel time of the base flows would have the potential of addressing this impact. I have chosen to focus on the use of bioswales due to them being commonly implemented within urban environments to slow water flow down. However, bioswales have not been regularly implemented in rural environments (Xiao & McPherson, 2011). Bioswales are commonly used within urban environments to control storm water runoff from impermeable surfaces such as roads and parking lots (Jurries, 2003). Bioswales are manmade depressions with a low gradient that are designed to slow surface water runoff in order to increase the rate of infiltration of the water into the ground (NRCS, 2005). By increasing the rate of infiltration a bioswale can be used to reduce surface water runoff and increase groundwater. Since ground water travels through a watershed more slowly than surface water this has the overall impact of increasing the travel time of water through a watershed. This would have the potential to directly counter the impacts of climate change and clear-cutting which are resulting in the base flow moving through the water systems earlier in the year. However, based on the current lack of bioswales being used outside of urban environments it is reasonable to question the effectiveness of bioswales within landscapes with low percentages of impermeable surfaces such as rural landscapes. My pilot study is directly addressing this concern by measuring the effectiveness of bioswales within a clearcut site. It should also be noted that bioswales have been used by alternative forestry and agricultural organizations to increase onsite water retention for the expressed purpose of transferring surface water flow to groundwater (Lancaster, 2013). In addition, a major US$252 million project in the Chinese Loess Plateau implemented a number of features similar to bioswales (terraces and other features that reduced the flow gradient and slowed the velocity of surface water flow) across a rural farming area of more than 2.5 million people that has dramatically reduced surface water flow and sediment runoff. Due to the success of this project at transforming a large area from degraded scrub-shrub and desert back to productive farmland it has since been replicated across China reaching over 20 million people (The World Bank, 2003). Based on the success of this technique in China and by alternative forestry and agricultural organizations within the United States it seems likely that the use of bioswales within clearcuts would result in the base flow of water being slowed resulting in an increase in the infiltration of surface water runoff to groundwater. While the research is not available to confirm this hypothesis, it seems likely that these techniques would have the impact, if implemented in the Western United States, of shifting the timing of the base flow later in the year. This would directly address the impacts of climate change and clear-cutting on base flows.

Currently, the use of bioswales or other methods aimed at slowing base flow through a water system has not been fully explored. However, there is ongoing research being conducted within the Olympic Experimental State Forest (OESF) in Washington State's Olympic Peninsula by the Washington State Department of Natural Resources (DNR) that is looking at the impact of techniques implemented under DNR's habitat Conservation Plan to enhance habitat availability for species such as the spotted owl (that were not optimized for water retention) and how they may reduce the impact of logging on water flow (WA DNR, 1997). These techniques involve implementing logging practices in a manner and distribution that mimics natural disruption events such as forest fires and are being monitored by making streamflow measurements to produce rating curves outlining the changes in streamflow over the course of a water year (October 1st through the end of the following September). While these techniques may prove to be effective within the study area at the conclusion of the study, their effectiveness may differ in other parts of the Western United States due to the streams studied in this report being mostly storm drive as opposed to snowmelt driven[2]. Natural disruption events will often leave pockets of trees standing resulting in islands of habitat within the disrupted area. Bioswales and other similar features could be implemented along with DNR's practices by placing the swales or other features in the fully logged areas outside of the "habitat islands."

Similar Methods and Techniques

While bioswales have not been actively implemented within forestry lands it should be noted that there are several techniques that are currently implemented as a part of normal forestry practices that actively slow surface water in a manner similar to

[2] Coastal watersheds are often driven by storm events while inland watersheds within the Western United States are mostly driven by spring snowmelt.

bioswales. During logging operations, it is common to install features known as pump chances and heli-ponds. Both of these features create pockets of water that can be used by firefighters to combat forest fires. Pump chances are essentially ponds that are constructed where a ditch or non-fish bearing stream enters a culvert. These pump chances can then be used by firefighters as a water source (Oregon State University, 2016)(figure 3). Pump chances have not been implemented as a tool for use by water managers to delay the base flow but given that the forest fire season in the Western United States is primarily during the summer months for a pump chance to be effective it would need to be able to retain water from the winter and spring. This indicates that the use of water retention features within rural environments might be effective. Heli-ponds (Helicopter ponds) are similar to pump chances and are large ponds that firefighter helicopters can use to collect water for their buckets. As with pump chances the use of heli-ponds indicates that water retention features can be successfully implemented within rural environments and more specifically forestry lands.

Figure 3: Pump Chance - (Oregon State University, 2016)

In addition to pump chances and heli-ponds, recently restoration organizations have been using beavers and the dams they create to actively retain and slow surface water within rural environments (Castro, Pollock, Jordan, Lewallen, & Woodruff, 2015). The Lands Council located in Spokane, Washington, has actively been using reintroduced beavers within the Colville National Forest to retain water within upper watersheds (Walker, et al., 2010). While the use of beavers is focused within streams and rivers, it is another example of the basic principle of retaining and slowing surface water within rural environments. In the specific case of The Lands Council's efforts, beavers are being used to directly impact the base flows in order to increase the availability of water during the summer months. The use of beavers, pump chances and heli-ponds all indicate the practical nature of actively managing forestry lands to slow surface water down and increase the available base flow.

Significance of the Pilot Study

The pilot study outlined within this report is focused on a specific case study at the University of Washington's Pack Forest, located near Eatonville, WA. This study seeks to address the gap in the literature on the effectiveness of bioswales at addressing the impact of clear-cutting on the base flow of water. If this study shows that bioswales are effective at increasing water retention it would indicate that features that slow surface water and increase infiltration rates could be a tool for water managers to use to increase the available base flow of water. As outlined in this report in order to address the impacts of climate change and land use practices on base flow a new set of tools beyond the traditional water management techniques (dams, etc.) and conservation techniques will be needed.

A large gap in the literature can be found around the use of active management techniques within working lands to slow the travel of water through these lands in order to increase the available base flow. With the oncoming crisis caused by climate change and the compounding impacts of land use practices the traditional ways of dealing with droughts and water shortages will not be enough. Water managers will need a new set of tools in order to meet the needs of cities, farms and others. While my research only focuses on a very small piece of this puzzle it is hoped that further research will be conducted to further fill the gap in the literature.

Methodology and Study Design

As outlined in the previous section water managers in the Western United States face the daunting task of providing adequate water for their communities in the midst of climate change and a growing population. Land use practices have a significant, though still understudied, impact on the base flow available for water managers to use and has created a system that is vulnerable to shocks such as droughts that are likely to become more common and more severe due to climate change. Addressing the impacts that land use practices have on the base flow is a new direction that this pilot study seeks to better understand through the analysis of a specific case study.

My pilot study focuses on better understanding the effectiveness of using bioswales for water retention within clearcut sites. Doing so will complete one small piece of the puzzle facing water managers today – how to provide adequate summer water supplies without negatively impacting the environment? As outlined in the literature review section bioswales are commonly used for stormwater runoff control within urban environments but have not been used in rural environments except in areas with high levels of impermeable surfaces. It should be noted that bioswales have been used by alternative forestry and farming organizations with apparent success but there are few quantified results in the peer-reviewed literature. By analyzing the effectiveness of bioswales at retaining water within a clearcut environment this study will aid in determining if this technique should be considered for implementation as a water retention feature in clearcuts. If the use of bioswales in clearcuts is effective at retaining water, then this would open up a new door for improving water supply within forestry lands and addressing the impacts of climate change.

Site Location and Pre-Study Work

The study site is located at the University of Washington Pack Forest in a previously forested area that was clearcut in January 2015. This site was chosen for several reasons: has a low gradient slope, two different soil characteristics, ease of access, general security, and land owner willingness to support a long term field study. The Pack Forest is an experimental forest which provided a great opportunity for this study. This site is within the Nisqually Watershed and is approximately 4 miles away from the town of Eatonville in Pierce County, Washington State.

During the clearcut process contractors working for the University of Washington installed a series of bioswales for this pilot study. These bioswales were installed in two sets with each set having three bioswales. The bioswales were designed to be approximately 2.5 feet deep and 20 feet in length with 5 feet between each bioswales. The bioswales were dug on contour to minimize the horizontal gradient within each bioswales in order to reduce erosion. It should be noted that the final bioswales were deeper than the design called for which resulted in several limitations that will be discussed later in detail.

During the course of this study the University of Washington has been running an additional study that involved planting Sitka spruce with each red cedar as part of the replanting plan. Deer commonly eat young red cedar and UW was researching if the Sitka spruce could minimize damage caused by the local deer population. Sitka spruce has sharp needles that deer tend to avoid eating it – the thought is that planting Sitka spruce with red cedar will protect the red cedar from being eaten. While this research involved planting more trees than would normally be planted it is unlikely that this would have a major impact on the pilot study since replanting is a common forestry practice within clearcut sites. In addition, the planted trees were less than a year old at the conclusion of the pilot study which would minimize any potential impact. Finally, the planting plan was done within the entire study site making any impact universal across the controls and the experimental sites.

Experimental Design

The pilot study was designed to have two sets of three bioswales with each set having a corresponding control with similar overall dimensions and soil characteristics. The two sets are labeled as Site A and Site B with the corresponding bioswales being collectively referred to as Ae and Be – short for Subsite A/B Experimental. The controls are referred to as Ac and Bc – short for Subsite A/B Control (figure 4).

Figure 4: Overview of pilot study – identical layout for both site A and B

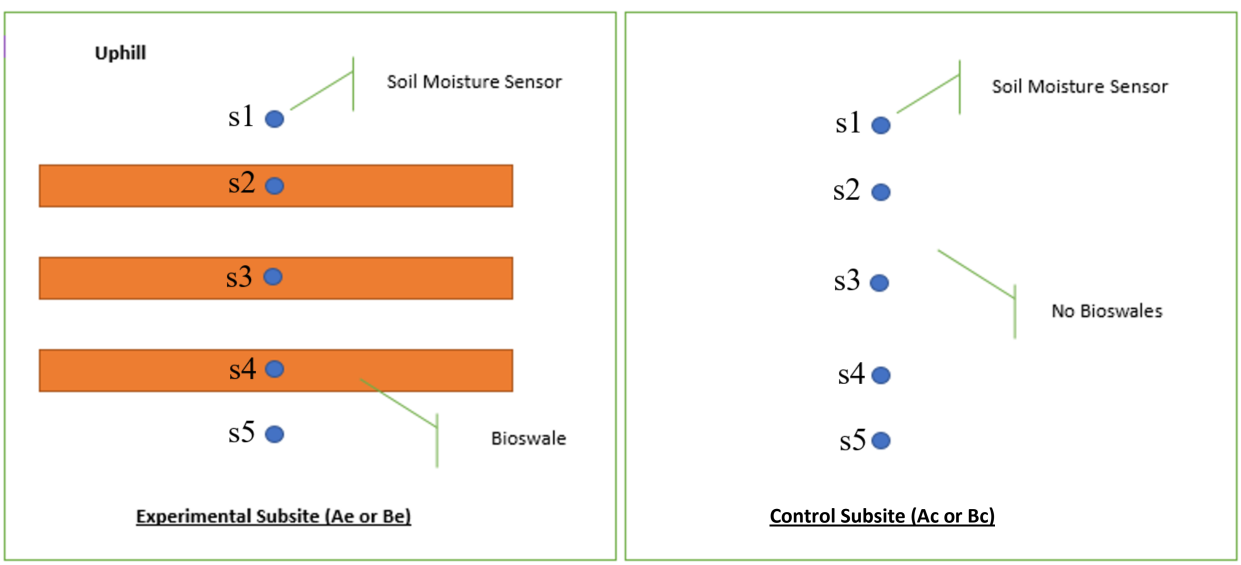
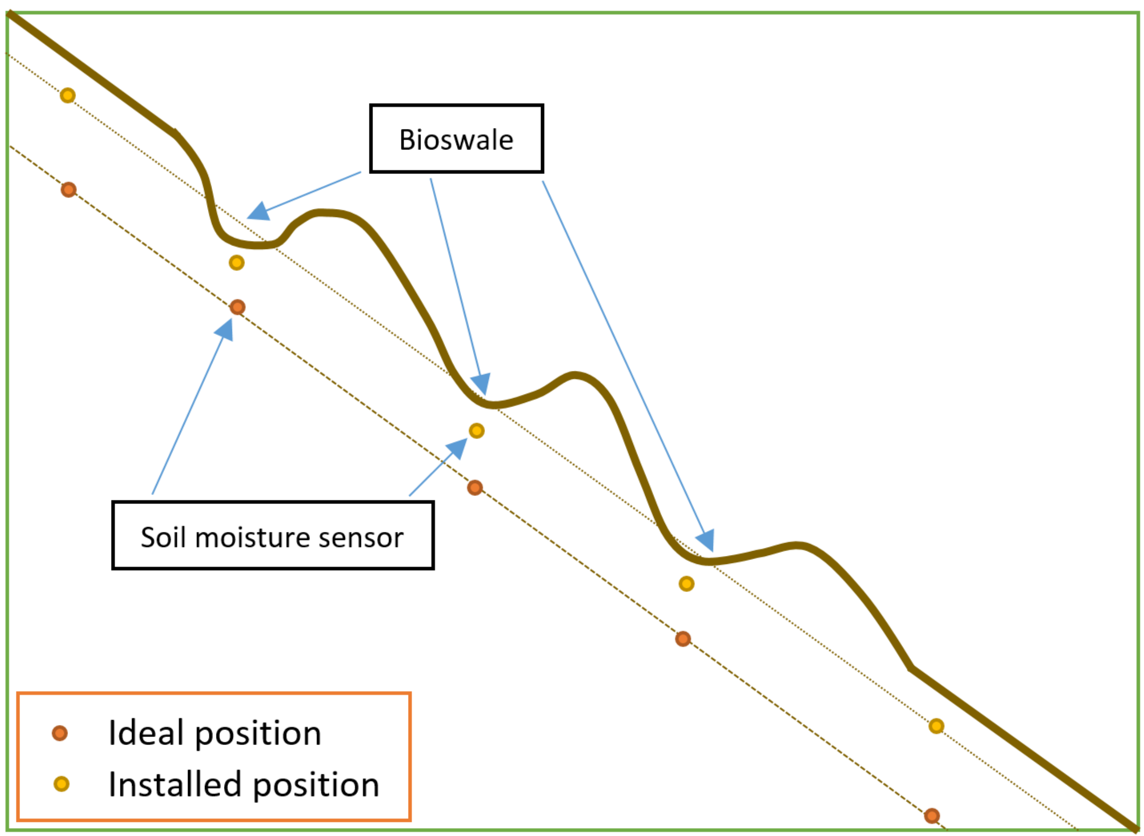


Figure 4 also shows the location of the soil moisture sensors that were installed to measure changes in soil moisture levels within each site. The layout of the soil moisture sensors is the same for each site. Each site also has a single data logger that records the soil moisture values from the sensors. In total 20 Decagon GS1 Ruggedized Soil Moisture Sensors combined with 5 Decagon Em50 Digital Data Logger were installed for this pilot study.

The soil moisture sensors were installed to measure the initial moisture level before the swales, the moisture level directly beneath each bioswale and the final moisture level after all three swales. Each sensor was installed in a hole approximately 2.5 feet deep using a posthole digger – it was not possible with available equipment to install the sensors deeper. If the sensors were installed at an ideal depth a line could be drawn

Figure 5:Ideal sensor layout compared to installed sensor layout



through each sensor that would have identical gradient to the unmodified slope (figure 5). This ideal was not reached due to limits in the ability to install sensors deeper than 2.5 feet (figure 5). It should be noted that despite the lack of ideal placement of the sensors the decision (explained in the limitations section of this thesis) to focus on the data from the furthest uphill sensors (s1) and the sensor below the first swale (s2) should minimize the negative impact of the install depth not meeting the ideal. The sensors were installed in each hole using best practices as outlined in the manual provided by the company that produced to sensors (Decagon Devices, Inc., 2015). This layout of sensors was chosen to capture changes in soil moisture in a downslope direction. It was assumed that the upper most swale within each experimental subsite would intercept surface water runoff from uphill with excess water cascading over the edge of the bioswale into the one further downhill. Based on site observations and images from the time-lapse cameras installed in each experimental subsite it appears that the water captured within the upper most swale in both site A and site B did not overflow into the downhill swale during the course of the study. The impact of the lack of overflow is covered within the limitations section of this report.

The sensors and data loggers were installed at the start of May 2015 and left to continually collect data over spring, summer and fall 2015. This timeline allows for the capturing of soil moisture levels from a point of saturation in spring, through summer minimums, and back to saturation with fall rain.

Finally, at the lowest swale within Site Ae and Be a time-lapse camera was installed to visually monitor the amount of surface water collecting within the corresponding swale. A staff gauge was installed in these swales as a visual aid to determine relative changes in water level through the pictures captured by the time-lapse camera. This setup allowed for a more detailed observational record of the impacts of the bioswales between site visits.

General Site Observations

The two sites are both within the same clearcut area but based on observations it appears that the soil conditions change between site A and site B. Care was taken to ensure that soil conditions were identical between the controls and the corresponding experimental sites during installation of the sensors and data logger. Site A's soils are characteristically well drained and made up of mostly gravel, sand and cobbles. During the course of the study no standing surface water was seen within Site A. Site B's soils are the opposite and are made up of silt, clay and sand. Surface water was often visible within the installed bioswales in subsite Be and within natural depressions and depressions created during logging surrounding Be and in the control Bc. These soil conditions may result in different behaviors for soil moisture between site A and site B. If the results from the collected data confirm the different soil characteristics of the two sites, then it may not be possible to conduct a comparison between the two sites.

Equipment Overview

Soil moisture sensors come in a variety of general types but as a whole have been used for research and testing purposes for over 50 years (Bureau of Reclamation, 2015). The GS1 sensors measure the change in resonant frequency between a pair of electrodes – this is referred to as a frequency domain reflectometry (FDR or capacitance) sensor. The advantage of this sensor type is that it is not impacted by soil salt levels or fertilizer levels

(Bureau of Reclamation, 2015). The GS1 sensor operates on a frequency of 70 MHz, is ruggedized and capable of operating underground over long time periods which was necessary for this study.

The Em50 digital data loggers have room for five soil moisture sensors and are designed to operate for a year before the batteries are drained. The Em50 is also weatherized which was a necessity for this study. The recorded data can be accessed using software provided by Decagon, Inc. with the purchase of the Em50. A windows based tablet was used to access the recorded data in the field.

Study Limitations

The initial experimental design called for recording soil moisture data from each of the five sensors per subsite. This would allow for the changes in soil moisture levels to be recorded over a spatial gradient moving downslope. Due to limitations in the equipment used to construct the bioswales, each bioswale was dug deeper than the design called for which resulted in the ideal install depth for each soil moisture sensor being greater than the available equipment could achieve. This also resulted in the water collected within the upper bioswale remaining trapped and not flowing from the top swale to the following downslope swale. Due to this impact of the construction and due to each swale being only approximately five feet apart only the upper most swale within each experimental subsite intercepted any meaningful volume of surface water runoff from the upper reaches of the clearcut. The lower bioswales are assumed to be only intercepting rainfall and potentially groundwater flow which was not a focus of this study. Based on this the data analysis will focus on the impact of the uppermost swale within experimental subsite. The remaining sensors were still installed and the corresponding data is available for comparison purposes and will be listed within the results section.

Data Collection

Soil moisture data collected by the GS1 soil moisture sensors was recorded by the Em50 data loggers once every 10 minutes each day for the duration of the study as volumetric water content measured as "m^3 of water" per "m^3 of soil". The 10-minute time interval was chosen in order to ensure that any changes in soil moisture values regardless of how small would be recorded by the data logger. The time lapse cameras were setup to take a picture once every 10 minutes during daylight hours.

Over the course of the pilot study the field site was visited once a month. During these visits all the data and pictures were downloaded using a windows tablet. The soil moisture data was downloaded as a separate Excel spreadsheet for each data logger. Each spreadsheet contains a table that records sensor values and the date/time the value was recorded for each sensor attached to the data logger. Site visits also included recording any observations about the condition of the sites. These observations will be covered in the discussion section of this report. Most field observations focus on the presence of amphibians and macro-invertebrates in the bioswales.

Data Analysis

Excel pivot tables was used to find the average volumetric water content per day for each soil moisture sensor. This reduces the total data points from a staggering 20,160 per week across the entire study to a more manageable 140 data points per week – 35 per data logger each week. The daily averages were then graphed by site – Ae, Ac, Be and

Bc. This allows for a simple comparison to be made and for behaviors to be determined. Graphs were produced for the full duration of the study and split by water year. The 2014-2015 water year data covers the time period from May 3rd/4th till September 30th 2015. The 2015-2016 water year data covers the time period from October 1st till December 19th 2015. While there is not complete data for a full water year, breaking the data by water years allows for a determination of the behavior expressed by each site during the transition from wet spring to dry summer (2014-2015 water year data) and during the transition from dry summer to wet fall (2015-2016 water year data).

The overall pattern for changes in soil moisture levels over the course of the pilot study was determined by tracking changes in volumetric water content from the furthest uphill sensor down to the lowest sensor. The controls allow for a determination of the pattern of changes in soil moisture within the control sites which can then be compared to the pattern of changes in soil moisture within the experimental sites. The timing and volume of the spring maximum volumetric water content and the timing and volume of the summer minimum volumetric water content was used in addition to the graphs to determine the behavior of soil moisture within each site. The results of the comparison of the patterns in the changes of soil moisture over the course of the pilot study can then be used to determine an answer to the original question: Can bioswales be implemented within clearcut sites to effectively retain water?

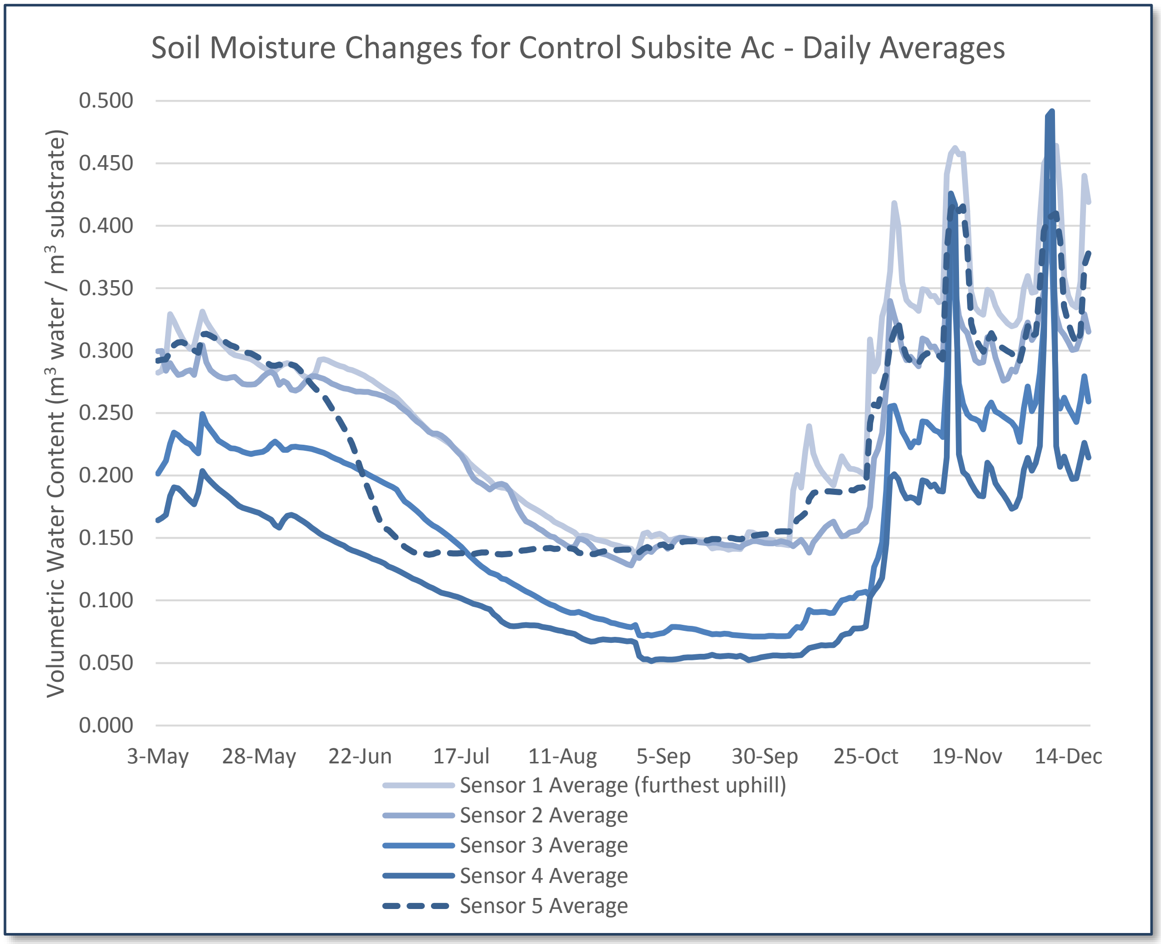
Results and Discussion

Results of this pilot study are broken into several subsections that first outline the pattern in the changes of soil moisture levels within the two control subsites (Ac and Bc). These subsections will provide a general overview of the recorded values for each subsite and list the maximum, minimum and timing of the soil moisture values for each of the subsites. These recorded values for the experimental subsites (Ae and Be) will then be compared to the values and timing found in the corresponding control subsite in order to determine an answer to this thesis's research question – are bioswales effective at increasing water retention with clearcut sites?

Soil Moisture Values and Timing for Control Subsites Ac and Bc

Control subsite Ac is made up of well-drained soils consisting of sand, gravel and some cobbles. Over the course of the pilot study changes in soil moisture level (volumetric water content) was recorded for each of the five sensors and shows a clear overall seasonal pattern responding to changes in precipitation (figure 6). For this analysis only the time period covering the 2014-2015 water year will be used due to this period covering spring to summer transition which is the most important from the view point of available base flow. Sensor 1 is located at the further uphill extent of subsite Ac, sensor 5 is located at the base of Ac. Subsite Ac has a pattern of decreasing volumetric water content moving in a downhill direction. This is consistent with the soil making up Ac being well drained – since the soil moisture sensors were installed at the same approximate depth, decreasing soil moisture levels would be consistent with the water moving at a more downward angle. It should be noted that sensor 5 (the furthest downhill sensor) does not express a consistent pattern of change compared to the other sensors. This could be due to a variety of reasons. The sensor could have been installed incorrectly; There could also be a change in the soil content at this point – With the limited data available as part of this study it is not possible to make an exact determination of the cause of this change. This overall pattern of soil moisture change will be used as a baseline to determine the impact of installing swales within experimental subsite Ae.

Figure 6: Soil moisture changes from May 3rd to December 19th 2015 for subsite Ac - Daily average



Dates and values for maximum and minimum soil moisture level was recorded for each sensor to serve as the baseline data to determine the impact of installing swales within experimental subsite Ae.

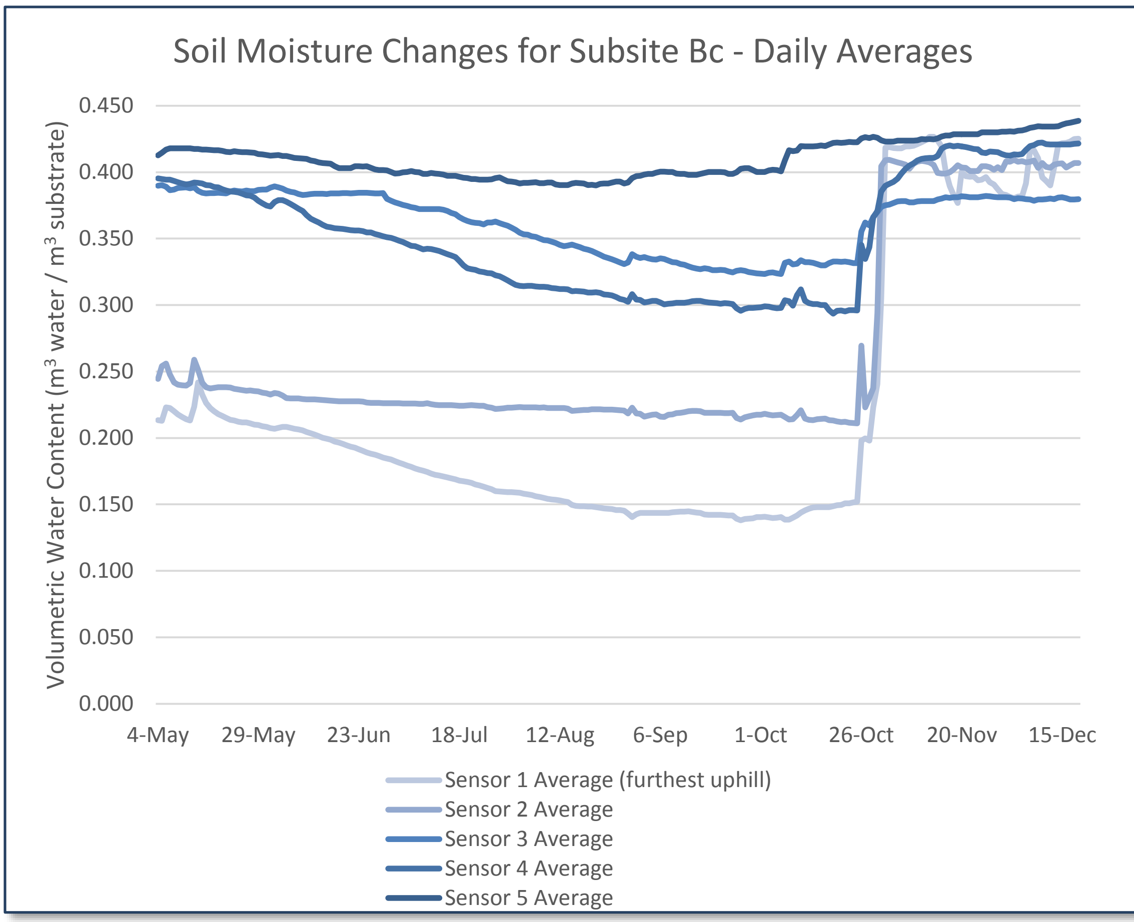
Table 1: Subsite Ac maximum and minimum soil moisture value and date reached for 2014-2015 water year

	Soil Moisture – Maximum		**Soil Moisture - Minimum**	
	Date	*Value (m³ water/ m³ soil)*	*Date*	*Value (m³ water/ m³ soil)*
Sensor 1	05/14/2015	0.331	08/29/2015	0.136
Sensor 2	05/14/2015	0.304	08/28/2015	0.128
Sensor 3	05/14/2015	0.249	09/30/2015	0.071
Sensor 4	05/14/2015	0.204	09/26/2015	0.052
Sensor 5	05/14/2015	0.314	09/19/2015	0.137

Maximum soil moisture for all sensors at Ac was reached on May 14th; minimum soil moisture for sensors showed some variation and occurred between Sept. 19th and 30th (table 1).

In contrast to control subsite Ac, subsite Bc consists of poorly drained soils – it was common during wet periods to see standing and flowing surface water within this control site. Over the course of the pilot study changes in soil moisture level (volumetric water content) was recorded for each of the five sensors and shows a clear overall seasonal pattern responding to changes in precipitation (figure 7). This seasonal pattern is clearly different from the pattern recorded for subsite Ac, likely due to the differences in the soil make up of subsite Bc compared to subsite Ac. As with subsite Ac this analysis will focus on the period covering water year 2014-2015. As with the previous results, this chart shows how soil moisture levels change overtime for each of the five sensors. Sensor 1 is located at the further uphill extent of subsite Bc, sensor 5 is located at the base of Bc. A clear overall pattern in the changes in soil moisture levels can be seen with soil moisture levels increasing in a downhill direction from sensor 1 to sensor 5 (figure 7). It should be noted that sensors 3 and 4 do not hold to this overall pattern but are still within the range of reasonable values. The overall pattern of increasing soil moisture content is consistent with more poorly drained soils which is expected from on the ground observations.

Figure 7: Soil moisture changes from May 4th through December 19th 2015 for subsite Bc - Daily average



Maximum soil moisture showed variation across the sensors set at subsite Bc and occurred between May 5th and 14th; minimum soil moisture for sensors also showed some variation and occurred between Sept. 21st and 30th (table 2). These values will serve as the baseline data to determine the impact of installing swales within experimental subsite

Be. The dates and values for the maximum and minimum soil moisture values match the overall pattern of changes in soil moisture values shown in figure 7.

Table 2: Subsite Bc maximum and minimum soil moisture value and date reached for 2014-2015 water year

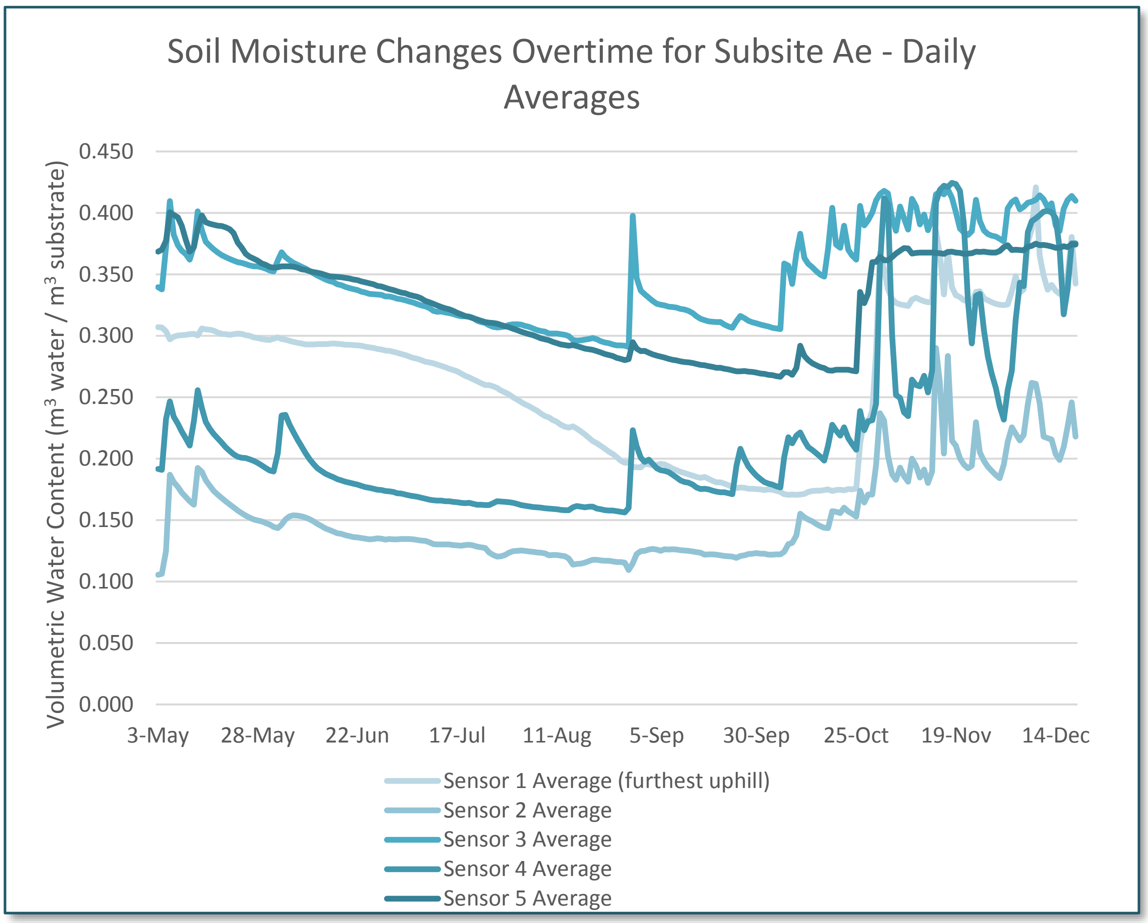
	Soil Moisture – Maximum		**Soil Moisture - Minimum**	
	Date	*Value (m^3 water/ m^3 soil)*	*Date*	*Value (m^3 water/ m^3 soil)*
Sensor 1	05/14/2015	0.242	09/26/2015	0.138
Sensor 2	05/13/2015	0.259	09/26/2015	0.214
Sensor 3	05/05/2015	0.390	09/30/2015	0.324
Sensor 4	05/05/2015	0.395	09/26/2015	0.296
Sensor 5	05/12/2015	0.418	09/21/2015	0.390

Soil Moisture Values and Timing for Experimental Subsites Ae and Be

The experimental subsites Ae and Be were placed adjacent to the respective control subsites in order to ensure that the soil types would be similar. Care was also taken to ensure that each experimental subsite had similar slope and other general characteristics. As stated earlier the swales in the experimental subsites are larger than initially planned which prevents water from cascading from an upper swale to a lower one. Due to this the water flow through the experimental sites would be only intercepted by the first uphill swale (sensor 2). The data from the remaining sensors will be included in the analysis but may not have resulted in useful data. Despite this limitation it will be possible to determine the impact of the first swale and potentially the overall impact of all three swales – each experimental subsite has a sensor (recorded as sensor 5) installed at the lowest point of the subsite.

Unlike the control subsites, soil moisture values within subsite Ae do not appear to change based on a recognizable pattern across the five sensors – sensor 1 has the third highest soil moisture value through the end of September 2015 except for a brief period at the start of September. Sensor 3 and 5 recorded the highest soil moisture values with sensor 3 ending the 2014-2015 water year at a higher value than sensor 5. Sensor 2 which was installed beneath the first swale consistently recorded the lowest soil moisture value for subsite Ae (figure 8).

Figure 8: Soil moisture changes from May 3rd to December 19th 2015 for subsite Ae - Daily average



Maximum soil moisture showed variation across the sensors set at subsite Bc and occurred between May 4th and 13th; minimum soil moisture for sensors also showed some variation and occurred between Sept. 21st and 30th (table 3). As with the previous chart no clear overall behavior can be seen from the data.

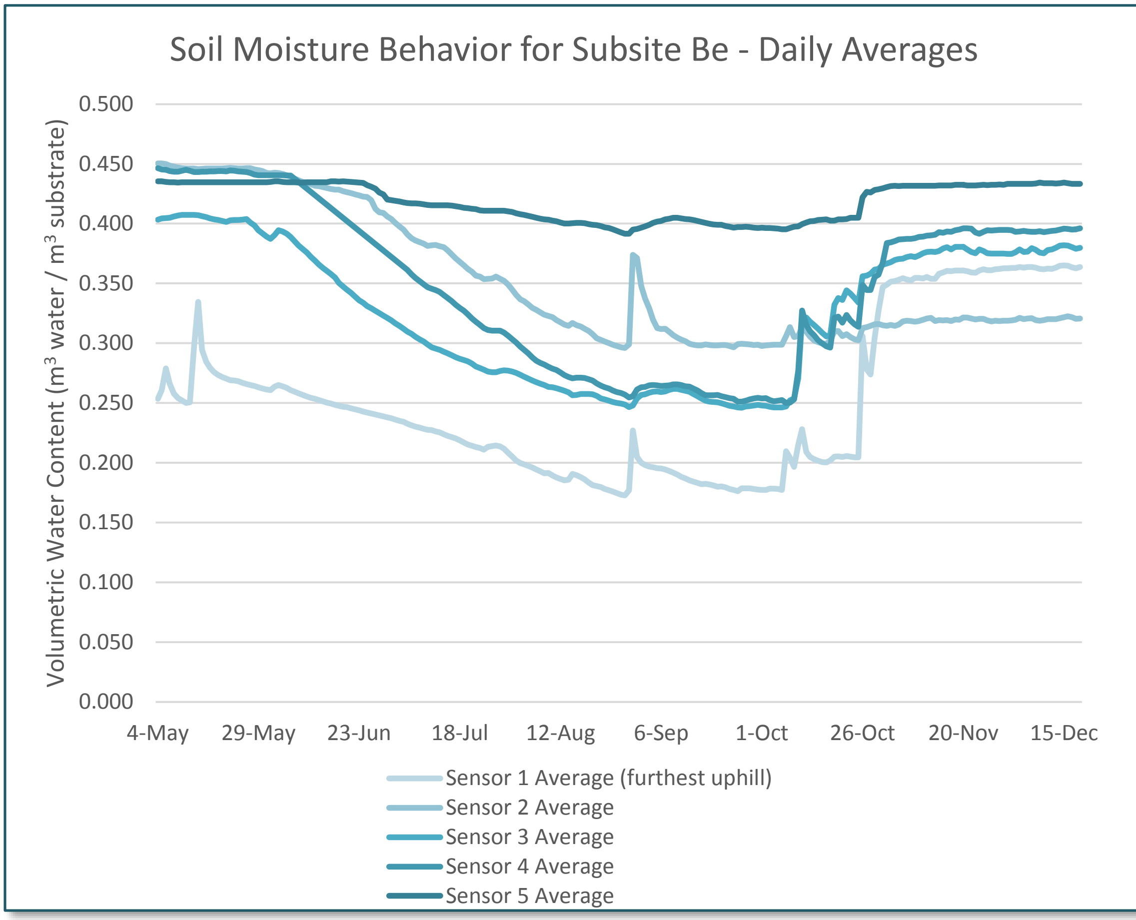
Table 3: Subsite Ae maximum and minimum soil moisture value and date reached for 2014-2015 water year

	Soil Moisture – Maximum		**Soil Moisture - Minimum**	
	Date	*Value (m^3 water/ m^3 soil)*	*Date*	*Value (m^3 water/ m^3 soil)*
Sensor 1	05/04/2015	0.307	09/30/2015	0.175
Sensor 2	05/13/2015	0.193	08/29/2015	0.109*
Sensor 3	05/06/2015	0.410	08/29/2015	0.291
Sensor 4	05/13/2015	0.256	08/28/2015	0.156
Sensor 5	05/06/2015	0.401	09/30/2015	0.270

** Lowest summer value – lowest overall value was 0.105 on 05/03/2015*

Soil moisture values for subsite Be show a clear overall pattern with soil moisture values increasing in a downhill direction (figure 9). It should be noted that sensors 3 and 4 show lower soil moisture values than sensor 2 but this could be explained due to the corresponding bioswale intercepting the majority of the surface flow. As stated earlier the bioswales were large enough that the furthest uphill swale for both Ae and Be could intercept any surface water flow without spilling over into the lower swales. Due to this any water intercepted by sensor 2 would slowly infiltrate into the ground likely resulting in this ground water moving too far below sensors 3 and 4 to be measured. Sensor 5 is further downhill in an area that slowly levels out which may allow this sensor to register the impact of the three uphill swales. However, due to the lack of overflow events within the uphill swales it is uncertain that the uphill swales would impact the values recorded by sensor 5.

Figure 9: Soil moisture changes from May 4th through December 19th for subsite Be - Daily average



Maximum soil moisture showed variation across the sensors set at subsite Bc and occurred between May 4th and 14th; minimum soil moisture for sensors also showed some variation and occurred between Aug. 28th and Sept. 29th (table 4). The values recorded in table 4 and in figure 9 will be used in the following discussion section to determine the overall effectiveness of the bioswales within subsite Be.

Table 4: Subsite Be maximum and minimum soil moisture value and date reached for 2014-2015 water year

	Soil Moisture – Maximum		**Soil Moisture - Minimum**	
	Date	*Value (m³ water/ m³ soil)*	*Date*	*Value (m³ water/ m³ soil)*
Sensor 1	05/14/2015	0.335	08/28/2015	0.173
Sensor 2	05/05/2015	0.451	08/28/2015	0.296
Sensor 3	05/14/2015	0.407	09/26/2015	0.246
Sensor 4	05/04/2015	0.446	09/26/2015	0.251
Sensor 5	05/05/2015	0.436	09/29/2015	0.392

Discussion and Analyses

The previous section focused on outlining the results from the pilot study – the following sections will compare these results in order to determine the overall significance of the pilot study and to determine if the research question was answered. Given that this is a pilot study this section will end with recommendations for next steps. These recommendations will focus on the next level of experimental data that needs to be collected and possible policy implications of this study.

The comparison of the results for each pair of subsites (Ac/Ae and Bc/Be) will focus on the timing of the peak and minimum soil moisture values and any relative differences in the corresponding soil moisture value at each point. Bioswales work by trapping and slowing surface water runoff resulting in an increase in the infiltration rate of surface water to groundwater. Thus, subsites Ae and Be should show relatively similar peak soil moisture values, higher minimum soil moisture values, a delayed decline from peak soil moisture and a delay in the timing of the minimum soil moisture compared to the corresponding control subsite. Due to the high levels of rainfall within the region it is assumed that soil moisture levels reach saturation during the peak time period. The bioswales would not be expected to increase the saturation point of the soils. Excess water would be trapped within the bioswales resulting in peak soil moisture declining at a slower rate than a site without bioswales. This slower decline should also result in a delay in the point of minimum soil moisture value and potentially a greater level of soil moisture at the minimum within the experimental subsites.

As explained earlier in this report due to the depth of the installed bioswales and the installed time lapse camera that there is no indication that the bioswales ever filled completely with water. Due to this any surface water runoff would have only been collected by the first bioswale (sensor 2 within the experimental subsites). Due to this only the soil moisture values from sensor 2 within each experimental subset would represent the interception of surface water runoff. As with the results section the full data for all the sensors will be shown for transparency but the analysis will focus on sensor 1, 2 and 5 within each site.

Comparison of the Results for Subsites Ac and Ae

The following table shows the results from subsite Ac and Ae side by side for a simple comparison. Each of the sensors for the subsites are listed within the table as S1-S5 split into pairs with the calculated difference between Ae and Ac following each pair (Ae minus Ac). If the control has a higher maximum or minimum the difference is marked negative and colored red to indicate a result counter to the expected result. The difference in the date the maximum and minimum was reached is marked and colored using the same code.

Table 5: Comparison of soil moisture values and corresponding timing across five sensor pairs for subsites Ac and Ae

	Maximum Soil Moisture Value ***m^3 water/ m^3 soil***	**Date Maximum Reached**	**Minimum Soil Moisture Value** ***m^3 water/ m^3 soil***	**Date Minimum Reached**
Ac S1	0.331	05/14/2015	0.136	08/29/2015
Ae S1	0.307	05/04/2015	0.175	09/30/2015
Diff	-0.024	-10 days	0.039	32 days
Ac S2	0.304	05/14/2015	0.128	08/28/2015
Ae S2	0.193	05/13/2015	0.109	08/29/2015
Diff	-0.111	-1 day	-0.019	1 day
Ac S3	0.249	05/14/2015	0.071	09/30/2015
Ae S3	0.410	05/06/2015	0.291	08/29/2015
Diff	0.161	-8 days	0.220	-32 days
Ac S4	0.204	05/14/2015	0.052	09/26/2015
Ae S4	0.256	05/13/2015	0.156	08/28/2015
Diff	0.052	-1 day	0.104	-29 days
Ac S5	0.314	05/14/2015	0.137	09/19/2015
Ae S5	0.401	05/06/2015	0.270	09/30/2015
Diff	0.087	-8 days	0.133	11 days

Comparison of the soil moisture values between sensors Ac S1 and Ae S1 indicate that the control subsite had a higher maximum soil moisture value but a lower minimum soil moisture value (table 5). Specifically, sensor Ac S1 recorded a maximum soil moisture value that was 7.82% greater than sensor Ae S1 and a minimum soil moisture value that was 22.3% less than sensor Ae S1. The reasons for the differences are unknown at this time. Sensor Ae S1 is located above the first bioswale within subsite Ae and should not be impacted by the bioswales. Both Ae and Ac were impacted by heavy equipment during the logging process prior to implementation of the study but the area around sensor Ae S1 was likely compacted during the digging of the first bioswale within subsite Ae. Based on observations during site visits this area appeared to have a greater level of disturbance than the control. This disturbance would have likely resulted in compaction of the soil that may have impacted the soil moisture levels. Comparing Ac S2 and Ae S2 show that the control had higher minimum and maximum soil moisture values than the experimental subsite. Sensor Ac S2 recorded a 57.5% higher maximum soil moisture level and a 17.4% higher minimum soil moisture level than recorded by sensor Ae S2. The differences in the timing of these values was not significant.

Based on this comparison it appears that the bioswales installed within subsite Ae had no positive impact on soil moisture values and potentially resulted in a negative impact. This indicates that there was little to no surface water runoff within site A – this is further indicated by the lack of visible surface water in the recorded time-lapse photos and from observations during site visits. The soil within site A is predominantly made up of sand, gravels and cobbles which would indicate a high natural infiltration level. The reduction in soil moisture levels seen within the experimental subsite could be caused by an increase in soil compaction which would decrease the ability of the soil to hold water and potentially an increase in the evaporation rate caused by the removal of surface plants and an overall increase in exposed surface area. From observations made during site visits subsite Ac had higher plant cover. These factors could have potentially resulted in the recorded decrease in soil moisture level.

Comparison of the Results for Subsites Bc and Be

As with the previous comparison the following table shows the results from subsite Bc and Be side by side for a simple comparison. Each of the sensors for the subsites are listed within the table as S1-S5 split into pairs with the calculated difference between Be and Bc following each pair (Be minus Bc). If the control has a higher maximum or minimum the difference is marked negative and colored red to indicate a result counter to the expected result. The difference in the date the maximum and minimum was reached is marked and colored using the same code.

Table 6: Comparison of soil moisture values and corresponding timing across five sensor pairs for subsites Bc and Be

	Maximum Soil Moisture Value *m^3 water/ m^3 soil*	**Date Maximum Reached**	**Minimum Soil Moisture Value** *m^3 water/ m^3 soil*	**Date Minimum Reached**
Bc S1	0.242	05/14/2015	0.138	09/26/2015
Be S1	0.335	05/05/2015	0.173	08/28/2015
Diff	0.093	-9 days	0.035	-29 days
Bc S2	0.259	05/13/2015	0.214	09/26/2015
Be S2	0.451	05/05/2015	0.296	08/28/2015
Diff	0.192	-8 days	0.082	-29 days
Bc S3	0.390	05/05/2015	0.324	09/30/2015
Be S3	0.407	05/14/2015	0.246	09/26/2015
Diff	0.017	9 days	-0.078	-4 days
Bc S4	0.395	05/05/2015	0.296	09/26/2015
Be S4	0.446	05/04/2015	0.251	09/26/2015
Diff	0.051	-1 day	-0.045	0 days
Bc S5	0.418	05/12/2015	0.390	09/21/2015
Be S5	0.436	05/05/2015	0.392	09/29/2015
Diff	0.018	-7 days	0.002	8 days

The comparison of sensors Bc S1 and Be S1indicates that subsite Be is an overall wetter area than the control Ac and that the maximum and minimum soil moisture values were reached earlier in the year in the experimental subsite (table 6). Specifically, sensor Be S1 recorded a maximum soil moisture value that was 27.8% greater than the value recorded by sensor Bc S1. Sensor Be S1 also recorded a minimum soil moisture value that was 20.2% greater than the value recorded by sensor Bc S1. This wetter pattern is also seen when sensors Bc S2 and Be S2 are compared – sensor Be S2 recorded a maximum soil moisture value that was 42.6% greater than recorded by sensor Bc S2 and a minimum soil moisture value that was 27.8% greater than recorded by sensor Bc S2. The difference in the timing for these values remained consistent for sensors Bc S1 – Be S1 and sensors Bc S2 – Be S2 indicating that the bioswales was not the cause of the timing difference between subsite Bc and Be.

Based on the comparison of Bc and Be it appears that the bioswales had a positive impact on soil moisture values within Site B. The soil characteristics within Site B is mostly clay and silt resulting in a relatively low natural infiltration level. Site observations and time-lapse photos both indicated flowing surface water following precipitation events and standing surface water within the bioswales through the end of June 2015. Despite the presence of standing surface water within the bioswales, no spill over event was recorded during the course of the study.

Significance of the Pilot Study and Recommended Next Steps

As outlined earlier bioswales have been traditionally used within urban sites with high amounts of impermeable surfaces. Within these urban environments bioswales intercept surface water runoff and increase infiltration rates resulting in an overall increase in water retention. This study focused on trying to answer the question of if bioswales would be effective within clearcut sites at increasing water retention. The results of this study were mixed and indicate that bioswales are effective at increasing water retention when soil characteristics of the site feature naturally low infiltration rates. This was the case with site B but the results of the pilot study also indicate that bioswales are poor at increasing water retention and may even decrease water retention within sites that feature naturally high infiltration rates as was the case with site A. It should be noted that despite the increase in soil moisture recorded within sub site Be compared to Bc there was no indication that bioswales delayed the timing of the summer minimum. Despite the lack of change in the timing of the summer minimum the results do indicate that bioswales are effective at increasing the volume of water retention within clearcut sites when soil characteristics feature relatively low infiltration rates but bioswales do not result in a delay in the timing of the summer minimum soil moisture level. This result is overall consistent with bioswales being predominately used within urban sites with high levels of impermeable surfaces.

As stated the results from the pilot study indicate that bioswales can be effectively used within clearcut sites with low levels of infiltration rates but the results do not indicate where the cutoff point is – that is at what infiltration rate do bioswales stop being effective? In addition, research should be expanded to include farmlands and other rural working lands in order to determine the full extent of the usefulness of bioswales at increasing water retention. Expanding and continuing the research would help determine if bioswales can function as a tool for water resource managers to use to address water supply needs in a changing world.

Conclusion

As outlined earlier in the report the Western United States is facing a difficult situation in regards to ensuring adequate water supply for human needs and for the natural environment. The useable base flow of water within the Western United States is being negatively impacted by climate change, land use change and demand for water from the communities across the region (Anderson & Woosley, Jr., 2005) (Defries & Enshleman, 2004). Traditionally, the useable base flow has been increased through the use of dams and other infrastructure that retain and capture the natural base flow. While the era of new dams is largely over due to a lack of building sites it is likely that existing dams will be enlarged and potentially new dams could be constructed in order to meet future water (Billington, Jackson, & Melosi, 2005). This is already taking place outside of San Diego in California and is being proposed near Yakima in Washington (US BLM, WA DOE, 2012). When faced with droughts and water shortage communities will demand something be done to ensure adequate water supply. Will this be done through traditional means such as increasing the size of existing dams or building new ones? Or will an alternative environmentally friendly path be taken to meet the needs of these communities? The research outlined in this report is meant to start the process of providing a new set of tools that can increase water supply without negatively impacting the natural environment.

The limited research conducted on the impact of land use change on water supply indicates that much of our land management practices are resulting in a reduction in the available water for human needs during the summer months. In addition, it is clear from talking with natural resource managers that it is accepted that human land use is negatively impacting the hydrological cycle. The difficulty in measuring these impacts is that any one land use change generally only has a small impact on its own – it is the cumulative impact of all the land use changes that result in a measureable negative impact on the hydrological cycle. These cumulative impacts are difficult to replicate in an experiment due to the scale of changes that are necessary. The result has been that most studies have focused on relatively small watersheds which are difficult to scale up to larger watersheds such as the Columbia River watershed and Colorado River watershed. Despite the limitations of existing studies to quantify the impacts it seems clear that adjusting our land use practices to have a positive impact on the hydrological cycle would provide a large benefit to communities across the Western United States.

Our traditional approaches to increase the useable base flow focus on a relatively small number of large and expensive infrastructure projects such as dams. As outlined above the negative impact of our land management practices are the result of a relatively large number of small and inexpensive practices that together have a major impact. The logging of a single 100-acre tract of land will have an impact but in isolation this impact would be contained to the immediate area. If this practice is duplicated across a watershed, then the impact stops being contained and can have a large measurable impact on downstream communities. While this example would likely result in a negative impact on these communities if new land management practices were adopted it may be possible to shift the impact from being negative to being positive. This is the driving force behind this research and is where future research needs to focus on – Can a large number of innovative, inexpensive, small and diverse land management practices be implemented across the working lands of the Western United States to increase the useable base flow and ensure adequate water supply?

The use of bioswales within clearcut sites is an example of a small and inexpensive land management practice that could be implemented where the site conditions warrant it. Other possible practices could include increasing the beaver population, farming on contour, expanding riparian buffers, and adopting new timber harvesting cycles to increase the average forest age. Such practices are numerous and each working land would require its own unique combination of practices that fit the characteristics of the specific site. What these practices should have in common is that they would be relatively simple to implement, inexpensive and would result in either an increase in water retention or a decrease in water consumption on site. While anyone practice at a particular site would have a small impact the cumulative impact of implementing these types of practices across all working lands within the Western United States could be substantial.

While a full policy outline is beyond the scope of this paper the following could be a basic way of setting up this system. At a state level, regulation would be established setting specific requirements for each county within the State to increase water retention and/or decrease water consumption within their working lands and urban areas. Funding for this effort would also need to be provided to the counties by a mix of State and Federal sources – ideally the Federal sources would provide funding to the State allowing the State to work directly with the counties. Each county would then work with the cities and private land owners within its boundaries to develop a mix of land use practices that together would reach the levels of water retention and conservation required by the State. Proposals for these land use practices could come from local cities and private land owners working in collaboration with conservation districts and local non-profits. The key for this program to work would be for the funding and mandate to come from the larger governmental bodies such as State and Federal governments and then be implemented by local institutions. Land management practices would be developed and run by a collaboration of local governments, private land owners, conservation districts and non-profits. Ideally, public Universities and Colleges would engage in research to better understand which practices were the most effective. The results of this research could then be shared through a nationwide database that would better enable communities to determine the best practices for increasing water retention and decreasing water consumption. The end result would ideally be a diverse web of small inexpensive land management practices implemented across the Western United States that would increase the resiliency of the region to the shocks of climate change and help ensure adequate water supply for the region.

Through this pilot study I have worked to provide a look at how forestry lands can be managed for increased water retention to protect summer water flows. Using bioswales within clearcuts for water retention should not be viewed as the end all solution – it is one tool for water resource managers to add to their tool box. Using bioswales is also a fairly simple technique that should not be a challenge to implement – the challenge will be for water and land managers and the rest of us to create a large set of diverse, innovative and simple tools that are tailored to specific local sites that can be implemented across the Western United States. By using a wide range of tools of simple tools for increasing water supply instead of a few complex tools we can create a much more resilient water system that is much less vulnerable to the shocks of droughts and other impacts of climate change.

Bibliography

Anderson, M. T., & Woosley, Jr., L. H. (2005). *Water Availability for the Western United States - Key Scientific Challenges.* Reston, Virginia: U.S. Geological Survey.

Andreassia, V. (2004). Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 1-27. doi:10.1016/j.jhydrol.2003.12.015

Bates, C., & Henry, A. (1928). Forest and streamflow experiment at Wagon Wheel Gap, Colorado. *Monthly Weather Review*, 1-79.

Billington, D. P., Jackson, D. C., & Melosi, M. V. (2005). *The History of Large Federal Dams: Planning, Design, and Construction.* Denver, CO: Bureau of Reclamation.

Blomquist, W., & Schlager, E. (2005). Political Pitfalls of Integrated Watershed Management. *Society and Natural Resources*, 101-117.

Bureau of Reclamation. (2015). *Weather- and Soil Moisture-Based Landscape Irrigation Scheduling Devices - Technical Review Report - 5th Edition.* Denver, CO and Temecula, CA: U.S. Department of the Interior.

Campbell, S., W addell, K., Gray, Andrew, & tech. eds. (2010). *Washington's forest resources, 2002–2006: five-year Forest Inventory and Analysis report.* Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Castro, J., Pollock, M., Jordan, C., Lewallen, G., & Woodruff, K. (2015). *The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains. Version 1.02.* Portland, Oregon: United States Fish and Wildlife

Service. Retrieved from http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp

Consensus Building Institute. (2012). *Water in the U.S. American West - 150 Years of Adaptive Strategies.* US Army Corps of Engineers. Retrieved from http://naturalresourcespolicy.org/docs/water-in-the-west.pdf

Cook, B. I., Ault, T. R., & Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, 1-7. doi:10.1126/sciadv.1400082

Decagon Devices, Inc. (2015). *GS1 Soil Moisture Sensor - Operator's Manual.* Pullman, WA: Decagon Devices, Inc.

Defries, R., & Enshleman, K. N. (2004). Land-use change and hydrologic processes: a major focus for the future. *Hydrological Processes*, 2183-2186.

Department of Ecology. (2014, March 6th). *Odessa Groundwater Replacement Program*. Retrieved from Office of Columbia River: http://www.ecy.wa.gov/programs/wr/cwp/cr_odessa.html

Field, C., Barros, V., Dokken, D., Mach, K., Mastrandrea, M., Bilir, T., . . . eds. (2014). *Summary for Policy makers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fith Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Fort, D., & Nelson, B. (2012). *Pipe Dreams: Water Supply Pipeline Projects in the West.* Washington, DC: Natural Resource Defense Council.

Fradkin, P. L. (1981). *A River No More - The Colorado River and the West* . Berkeley, CA: UNIVERSITY OF CALIFORNIA PRESS.

Georgakakos, A., Fleming, P., Dettinger, M., Peters-Lidard, C., Richmond, T., Reckhow, K., . . . Yates, D. (2014). *Ch. 3: Water Resources. Climate Change Impacts in the United States: The Third National Climate Assessment.* U.S. Global Change Research Program, U.S. National Climate Assessment. Washington, DC: U.S. Government Printing Office. doi:10.7930/J0G44N6T

Griffen, D., & Anchukaitis, K. J. (2014, December 28th). How unusual is the 2012–2014 California drought? *Geophysical Research Letters, 41*(24), 9017-9023.

Heathcote, I. W. (2009). *Integrated watershed management: Principles and Practice.* Hoboken, NJ: John Wiley & Sons, Inc.

Ingwersen, J. B. (1985). Fog Drip, Water Yield, and Timber Harvesting in the Bull Run Municipal Watershed, Oregon. *Water Resources Bulleting - American Water Resources Association*, 469-473. Retrieved from http://and.lternet.edu/lter/pubs/pdf/pub677.pdf

Johnson, R. (1998). The forest cycle and low river flows: a review of UK and international studies. *Forest Ecology and Management*, 1-7. doi:10.1016/S0378-1127(98)00231-X

Jurries, D. (2003). *Biofilters (Bioswales, Vegetative Buffers, & Constructed Wetlands) For Storm Water Discharge Pollution Removal*. Portland, OR: State of Oregon Department of Environmental Quality.

Lancaster, B. (2013). The Man Who Farms Water and the Rainwater-Harvesting Guidelines. In B. Lancaster, *Rainwater Harvesting for Drylands and Beyond* (pp. 23-29). Tucson, AZ: Rainsource Press.

Littell, J. S., Oneil, E. E., McKenzie, D., Hicke, J. A., Lutz, J. A., Norheim, R. A., & Elsner, M. M. (2010). Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climate Change, 102*(1), 129-158. doi:10.1007/s10584-010-9858-x

Marcum, D., & Gauthier, R. (2015). *#drylandsCA*. Retrieved from LA Times: http://drylandsca.latimes.com/

McGuinness, J. L., & Harrold, L. L. (1971). Reforestation Influences on Small Watershed Streamflow. *Water Resources Research*, 845-852. doi:10.1029/WR007i004p00845

Mckane, B., Benson, L., Brookes, A., Djang, K., Halama, J., Pettus, P., . . . Barnhart., B. (2015, May). Can longer forest harvest intervals increase summer streamflow for salmon recovery? Vancouver, WA.

NRCS. (2005). *Bioswales.* Washington D.C.: NRCS USDA.

Oregon State University. (2016, January 24). *Water Resources*. Retrieved from Oregon Forest Management Planning: http://outreach.oregonstate.edu/programs/forestry/oregon-forest-management-planning/plan-writing-tools-and-guidance/oregon-uniform-plan-guidelines/p-1

San Diego County Water Authority. (2015). *Emergency Storage Project - Building Water Reliability.* San Diego, CA: San Diego County Water Authority.

Scott, D. F., & Lesch, W. (1997). Streamflow responses to afforestation with Eucalyptus grandis and Pinus patula and to felling in the Mokobulaan experimental catchments, South Africa. *Journal of Hydrology*, 360-377. doi:10.1016/S0022-1694(96)03336-7

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in Snowmelt Runoff Timing in Western North America Under A 'Business as Usual' Climate Change Scenario. *Climatic Change*, 217-232.

The World Bank. (2003). *IMPLEMENTATION COMPLETION REPORT (IDA-26160) ON A CREDIT IN THE AMOUNT OF SDR 106.3 MILLION (US$ 150 MILLION EQUIVALENT) TO THE PEOPLE'S REPUBLIC OF CHINA FOR A LOESS PLATEAU WATERSHED REHABILITATION PROJECT.* East Asia and Pacific Region: The World Bank - Rural Development and Natural Resources Sector Unit.

Troendle, C. A., & King, R. M. (1985). The Effect of Timber Harvest on the Fool Creek Watershed, 30 Years Later. *Water Resources Research*, 1915-1922. Retrieved from http://www.wou.edu/las/physci/taylor/g473/refs/troendle_king_1985.pdf

US BLM, WA DOE. (2012). *Yakima River Basin Integrated Water Resource Management Plan.* Yakima, WA: US Department of the Interior, Washington State Department of Ecology.

WA DNR. (1997). *Final Habitat Conservation Plan.* Olympia, WA: WA Department of Natural Resources.

Walker, B., Parrish, A., Petersen, M., Martin, A., Morningstar, O., & Hall, K. (2010). *An Innovative Solution for Water Storage and Increased Late Summer Flows in the Columbia River Basin.* Spokane, WA: The Lands Council.

Xiao, Q., & McPherson, E. (2011). Performance of engineered soil and trees in a parking lot bioswale. *Urban Water Journal*, 241-253.