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With too many demands placed on too little water, the Klamath Basin and its residents - human and otherwise - are in dire need. There exists a significant opportunity for mitigation in the purposeful conversion of seasonal wetlands to permanent wetlands managed to increase baseline water storage levels in the Upper Basin. A thirteen-year survey of Landsat data coupled with contemporary flow information and a semi-autonomous classification method shows that more than 37,000 acres exist in the Upper Klamath Basin that naturally flood when water is plentiful, and so would have a natural advantage as storage mediums to buffer the time of maximum availability further into the summer, possibly retaining up to 60,000 acre-feet of water - nearly a 10% increase over baseline storage capacity. Managing these lands to maximize storage capacity would require policy changes in the basin targeted on both public and private lands. Public lands management for this objective would reduce available National Wildlife Refuge land that is currently leased to area farmers, while private lands management for this purpose would require an effort to provide incentives for voluntary participation, likely the enrollment of affected lands in federal conservation easements under the USDA and a regional water bank/market system. In either the public or private case, such a policy must be presented to regional stakeholders while considering their cultural values.

Surface Water Variation and Water Storage Potential in Upper Klamath Basin, 2000-2012

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Andrew M. Tanner, Author

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Chapter 1 Introduction

The Klamath Basin watershed has been the scene of one of the most divisive battles over water allocations in the American West. In 2001, the conjoined impacts of a drought and simmering political angst led to an outbreak of vitriol and struggle sometimes characterized as a ‘water war.’ The fundamental cause of this conflict is clear: seasonal water scarcity - here defined as too little water to meet the requirements of all users – particularly during droughts. Endangered species protection, agricultural irrigation diversions, waterfowl migration support, and salmon health all require sufficient quantities of water to be provided by the watershed. As climate change is expected to increase drought risk, and joint water requirements will likely increase over time, there is a pressing need to come up with equitable management options that can help reduce water conflict in the Klamath Basin.

This thesis posits that increasing wetland water storage capabilities in the Upper Klamath Basin (UKB) can provide a non-trivial means of mitigating some water scarcity, protecting approximately $8 million in agricultural productivity during drought years. Water shortages in UKB are predominantly seasonal: due to the geography of the Klamath Basin, the majority of available water passes through and out of the watershed in spring, during and after melting of the Cascade snowpack. However, water requirements stay high through the summer, leading to temporally based shortages. Increasing the extent of wetlands in the UKB could conceivably help alleviate summer shortages by providing a natural buffer of peak in stream flows: a network of wetland-based water storage systems that delay the movement of water towards the main stem of the Klamath and so keep it in the upper reaches of the watershed until later in the year when it is in greater demand. Increasing wetlands would additionally bring positive environmental side benefits due to the wide variety of ecosystem services wetlands provide, providing a potential advantage over reservoir storage.

This work uses satellite data from 2000-2012 to identify how much of the Upper Klamath Basin is prone to naturally flood during the wet season, as well as how much remains flooded through the dry summer. It uses the difference in these measurements to estimate the typical extent of wetlands in the area, and how their spatial extent has changed during the temporal period under consideration. Together with the general tendency of areas that naturally flood to retain water relative to those that don't, this dynamic can be exploited to estimate the extent of lands that would be best suited, in physical terms, for storing water into and through the summer. The satellite data is layered to identify areas where UKB wetlands tend to be located, which is key in understanding the policy limitations that would affect their being managed to maximize water storage.

To understand the volume of water that is seasonally surplus and so potentially available to be stored to offset shortages in later seasons, published literature and long term measurement of in-stream flows conducted by the US Geological Survey (USGS) are coupled to identify the amount of water available in both typical and atypical years, and the typical losses to evaporation and soil absorption inevitable in storing water on a permeable substrate. Together with the area estimate obtained from the satellite data, the volume estimate enables a reasonable description of the amount and location of water storage that could be feasibly generated via an active management strategy.

Research literature pertinent to wetlands, water storage, and other ecosystem services associated with wetlands, along with the specific nature of the basin's geographic particularities, is used to assess the likely direct and indirect physical impacts on the basin of restoring or converting the wetlands identified for the purpose of water storage. Research literature as well as theoretical approaches in natural resource policy will be coupled to discuss how instituting a storage policy that covers all surface waters with a propensity to naturally flood could be initiated, supported, and sustained in the face of legal, social, and political challenges.

Ultimately, the viability of utilizing wetlands for achieving increased water storage will be determined by local stakeholders and established processes, but it is hoped that this thesis will provide a valuable discussion of one reasonable pathway towards improving conditions in the area.

Chapter 2 Review of Literature

This literature review encompasses three major themes. First, a background on the basin's history and nature will be presented along with a discussion of the unique geography of the Klamath Basin and the characteristics of its wetlands. Second, discussion turns to an overview of the many ecosystem services wetlands typically provide where they are present, including the specific ecosystem service of water storage in wetlands that is of primary interest here. Third, an overview of some pertinent aspects of the spatial considerations in conservation policy will shed some light on how rough spatial groupings can impact conservation, restoration, and management of ecosystem services in the area.

2.1 Background on Klamath Geography and Wetlands

Klamath is a particularly interesting region because of its unique combination of climate, geography, and history of human influence. The basin itself is located in the eastern rain shadow of the Cascade Mountains, and is fairly arid, dependent upon annual precipitation for its water (Campbell, et al., 2001). However, despite this natural aridity, the Klamath Basin historically hosted an extensive network of wetlands and shallow lakes, connected by a network of rivers and streams that passed through the Cascade Range to reach the Pacific Ocean (Flug and Campbell, 2005). This concentration of groundwater gave rise to a highly productive ecosystem: salmon spawned in the watershed; waterfowl migrated, wintered, and nested in the wetlands; ruminant herds and their predators roamed the landscape.

The most physically imposing feature of the area, and the primary determinant of its hydrological peculiarities, is the line of peaks to the west - the Cascade Mountains (Flint & Flint, 2008). These, the result of millenia of volcanic activity and the clash of crustal plates, create a rainshadow to the east, which reduces the amount of precipitation Klamath receives. The lack of precipitation only worsens in the eastern portions of the watershed, where, by the time the Klamath Basin has crossed the border between Oregon's Klamath County and California's Modoc County, the watershed has extended into the high desert of the Great Basin (Tale et al., 2005).

UKB's water primarily originates as snowmelt from the Cascades, supplemented by rainfall (Burke et al., 2004). Its hydrological cycle is thus intimately linked with the climate of the Cascades, and much of the sediment and soil present in the basin has been deposited by water eroding volcanic mountains. The waters and soils of the Upper Klamath Basin are, because of the nature of volcanic rock, naturally enriched in the nutrients phosphorous and nitrogen (Eilers, et al., 2003, Duff et al., 2009).

European settlers arrived recently in both geological and cultural history, but their impact was soon widely felt (Eilers, et al., 2003). The traditional mode of landscape planning in Europe involves heavy modification of waterways and fields to better serve the needs of settled agriculturalists, and wetlands in particular were once singled out as landscapes that served little perceived purpose in their natural state (Mitsch and Gosselink, 2000). In part due to their natural ecological productivity, and in part to cultural biases, UKB wetlands were systematically diked, drained, and cultivated by Euro-American settlers after the 19th Century.

In the first half of the 20th Century, mass modification of UKB accelerated as population increased in the west, demands for hydropower grew apace with population, and agricultural use of lands exploded. Wetlands were aggressively converted to cropland, the Klamath River along with its many tributaries was dammed to create reservoirs and power infrastructure, and the 'Klamath Reclamation Project' was initiated by the federal government to convert wetlands into agricultural lands (Flug and Campbell, 2005). The widespread use of fertilizers that began with the 'Green Revolution' exacerbated the natural eutrophic nature of the UKB groundwater, leading to major blooms of algae in the largest body of groundwater in the area, Klamath Lake (Eilers, et al., 2003). In addition, the wide swaths of land planted with grasses to support meat and dairy cattle poured additional nutrients into the watershed via manure (Ciotti, et al, 2010). As a result of dam construction for flood management, water storage, and hydropower generation, salmon were no longer able to freely migrate to their spawning grounds in upper reaches of the watershed. This had the effect of decimating what was once the third most productive salmon fishery on the US Pacific Coast (Flint and Flint, 2008). Due to the ongoing degradation of their habitat (Cooperman and Markle, 2004), two indigenous fish species, the Shortnose Sucker and Lost River sucker, were pushed to the brink of extinction. With the loss of the wetlands the region was stripped of much of its capacity to absorb nutrients, so that the naturally eutrophic waters were enhanced by agricultural runoff to the point that many areas are now described by scientists as being hyper-eutrophic (Eilers, et al., 2004). With the expansion of human activities throughout the basin, and the concurrent increase in anthropic demand for water, the risk of catastrophic drought has grown (Burke et al., 2004).

In 2001, the Klamath Basin was the scene of one of the more acrimonious struggles over water allocations to take place in the modern American West. For policymakers who seek to mitigate the impacts of environmental variability and future climate change, the case of the Klamath ‘Water Wars’ (Owen, 2008, Doremus & Tarlock 2008) is instructive. Fortunately for the inhabitants of the region and anyone else interested in promoting stakeholder involvement in resource management decisions, there has been much progress in helping to restore the region’s ecology such that all its inhabitants’ interests are preserved (Gosnell and Kelly, 2010). Coming up with a workable policy that positively impacts baseline water availability in the Upper Basin would go a long way towards avoiding struggles in the future that could conceivably undermine the progress made thus far, notably in the collaboratively generated Klamath Basin Restoration Agreement.

Upper Klamath is home to a wide variety of species, some of which are found nowhere else. In particular, the region is home to two species of fish, the aforementioned suckers, whose ranges are so impacted that they are in danger of becoming extinct (Crandall et al., 2008). Steelhead and Redband trout are common in the streams and lakes of Klamath, and salmon travel as far upriver as the numerous dams allow (Tale et al., 2005). In the days before significant human modification of the landscape, Klamath’s status as one of the most productive salmon fisheries on the west coast of North America (Flint & Flint, 2008) has long supported First People in significant numbers. Birds are also a common sight in the area, with various species using Klamath as a home, breeding ground, or stopover point during migratory periods. Waterfowl, in particular, are one of the most numerous inhabitants in Klamath for much of the year, as the wetlands and fields of the basin are a vital staging ground for ducks and geese that travel north and south, following the seasonal change in weather (Eli & Takekawa, 1996). The migration of the waterfowl makes Klamath a crucial link between ecological regions along the Pacific Flyway, particularly the California Central Valley (Fleskes et al., 2010).

As with many ecosystems, there are two significantly limiting factors that control the ability of species to survive and thrive in Klamath: water, and availability of food (Cooperman & Markle, 2004). The two are inextricably linked, and areas where water and availability of food go hand in hand, such as wetlands and lake or river edge riparian zones, are of extreme importance to species that live in and outside the water. The loss of critical habitat zones is one of the major drivers of species loss around the world, and is likewise a driver of the reduction in species diversity and populations in Klamath (Crandall et al., 2008).

Loss of habitat isn't the sole danger facing the ecosystem. Since large scale Euro-American habitation began in the 19th century, massive alterations have been made to the original landscape - some intentional, others accidental. One of the more far-reaching changes has been to the nutrient cycle. Carbon, nitrogen, phosphorous, trace minerals, and metals have long entered the UKB watershed as a result of erosion in the area's volcanic soils, the decay of organic matter, and deposition in rainwater (Eilers et al., 2003). They move through the ecosystem along a variety of timescales, some being taken up in plants, others sequestering in soils. The natural evolution of the ecosystem has taken into account the historic availability of these elements and compounds, and the living things dependent on them have as well. But the introduction of intensive, fertilized agriculture has induced dramatic changes in these natural cycles (Diebel et al., 2008). A naturally eutrophic region has been inundated with P and N especially, causing a strong susceptibility to blooms of algae and other vegetative species that were not formerly dominant, and whose growth alters the ecosystem (Eilers et al., 2003). Klamath now exhibits twice the N concentrations in bio-available sentiment than formerly, and a 75% increase in concentrations of usable P (Ardon et al., 2010).

The effect of changing the makeup of the local ecology has more of an effect than simply altering the dominant species in a given area. The alteration in species that has taken place with high rapidity in the region has had detrimental effects on the dissolved oxygen present in the water of wetlands, rivers, and lakes (Sullivan et al., 2009). Dissolved oxygen is one of the more important measures of how well a body of water can support aquatic life. Fish require a sufficient quantity of oxygen in order to thrive, and their supply comes from oxygen dissolved in the water they inhabit. Major algal blooms, however, tend to decrease the level of dissolved oxygen available to other species, and in summer the water bodies of the region often become harsh habitats for fish that evolved to thrive in an ecosystem that long boasted a different set of parameters (Sullivan et al., 2009).

A significant factor in the deterioration of the Klamath ecosystem has been the loss of the majority of its wetlands over the past 150 years. Like the California Central

Valley, the Klamath Basin has been diked, drained, and otherwise deprived of its wetlands since Euro-American settlement began in earnest. Fortunately, where the proximity to major cities and transportation infrastructure likely played a major role in the destruction of 95% of the Central Valley's wetlands, Klamath lost closer to 60% of its native wetland inventory (Smith et al., 2008). This comes to nearly 45000 hectares (110,000 acres) during the period from the start of reliable record to 1999 (Eilers et al., 2003). The reason for this destruction is simple: wetlands are a highly productive ecosystem, and for good reason - they are exceptionally productive due to their high concentration of otherwise scarce minerals and nutrients, and what is good for native species tends to be good for introduced agricultural commodities (Eilers et al., 2003, Smith et al., 2008).

This wetland loss is linked to a wider scale degradation of the ecosystem over the past century. The recognition of the vital importance of wetlands has been made widespread in the sciences only in relatively recent times (Mitsch and Gosselink, 2000). Indeed, the very definition of a wetland is not entirely a matter of agreement in scholarly circles, and state agencies responsible for managing wetlands often have different functional definitions (Mitsch and Gosselink, 2000). Perhaps the most widespread definition stems from a convention, signed at Ramsar in Iran, which focuses largely on the depth of the water in the wetland - less than 6m (Zedler et al., 2005). Generally, however, the functional definitions used rely on the hydric quality of the underlying soils, the presence of water during some part of the year, and the particular emergent vegetation present in the area (Zedler et al., 2005).

The importance of wetlands is seen in how they have often been likened to nature's kidneys - one of their primary ecological functions is to act as filters for sediment, nutrients, organics, minerals, and even heavy metals that enter the watershed. But as wetlands are lost, the removal of the ecological functions they provide couples with an increased requirement for the very functions they once provided. Burning fossil fuels, disposal of human waste, and agricultural runoff are all major contributors to increased loads placed on the environment (Ardon et al., 2010). Sedimentation processes, plant uptake, and mineral adsorption all help wetlands mitigate this problem, and in fact wetlands are generally highly efficient in this regard - even when they don't physically sequester the contaminants responsible for ecosystem degradation, they often change these compounds' form to be less bio-available (Ardon et al., 2010). The efficiency and efficacy of wetlands in performing these functions has been noted in a growing number of scientific studies. Although natural wetlands are inevitably superior to restored or constructed wetlands, virtually all wetlands will serve to take phosphorous and nitrogen out of the environment (Mustafa & Scholz, 2010). Both plants and soils serve as sequestration points for the contaminants in the inflow waters, as well as carbon and heavy metals that themselves can function as adsorption points for contaminants (Mustafa & Scholz, 2010).

The loss of half of Klamath's wetlands has clearly impaired the ability of the region to absorb the excesses resulting from human impacts. Where wetlands have been preserved, they have routinely been managed with an overwhelming focus on maintaining static conditions not prevalent in nature (Smith et al., 2008). They have also run up against competition from water users with different interests, resulting in a long term reduction in the amount of water dedicated to the maintenance of hydric soils in wetlands (Smith et al., 2008). Wetlands in the area have historically been highly interconnected with, and in some ways dependent upon, the natural hydrology, which has been badly disrupted by land use change. This has resulted in isolation of many wetlands, and the relegation of others to being overwhelmed by the sheer changes wrought upon the landscape (Smith et al., 2008). The specific magnitude in a given area depends on local conditions such as hydrology, the use of surrounding lands, and even weather conditions. In one wetland adjacent to a dairy pasture, the runoff associated with a hundred cattle grazing on around seventy hectares increased N concentrations to 7.7 times background, and this rose to be in excess of 33 times background during a significant storm event (Ciotti et al., 2010).

During the period of interest for this study, droughts have played their own role in the changing environment of the Klamath Basin. The water in the basin drains towards the Klamath River, and are often entrapped by wetlands and lakes en route. The majority of the flows themselves arise as a result of melting snow in the Cascades and other high elevation areas, or as rainfall runoff. In years where the snowpack is below average, the end result is a decrease in the volume of water making its way to the Pacific during spring and summer. 2001-2002 saw a serious drought which caused decreased flows through the basin and thus decreased wetland coverage (Burke et al., 2004). This sort of event impacts the entire watershed - habitat decreases, wetland function declines, lake water levels go down, average temperature increases, and the concentration of contaminants in the remaining water goes up. The economy of the region was also severely impacted, due to the death of thousands of fish and a reduction in habitat space for migrating waterfowl (Burke et al., 2004). All the regional stakeholders were affected, from tribes to farmers to conservationists to ranchers, and the repercussions led to efforts to mitigate future drought effects; water banks, stakeholder meetings, and further regulations were all explored (Burke et al., 2004).

Currently, although restoration efforts by non profits and the work of federal agencies to provide appropriate incentives such as the Wetland Reserve Program and Conservation Reserve Program (Gleason et al., 2011) have been underway for many years, the full function of restored wetlands likely won't be realized for decades to come (Moreno-Mateos et al., 2012). The remaining natural wetlands that receive the most stringent protection are located along the shores of the Upper Klamath Lake, the Klamath Marsh, the Tule Lake, and the Lower Klamath National Wildlife Refuge Complexes. Lower Klamath in particular has been the scene of several studies of wetland function, and on the approximately five thousand hectares of seasonally flooded wetlands on the complex, major retention of sediments, P, and N has been observed (Mayer & Thomasson, 2004). These seasonal wetlands are primarily used to support waterfowl populations during the fall migration, and are flooded during the fall run up to the migration season, with around half the water allocated to them going to saturate the underlying soils (Mayer & Thomasson, 2004). They use approximately the same quantity of water per year as do the few permanently flooded wetlands in Lower Klamath, even though these latter wetlands suffer evapotranspiration losses in the hot summer months (Mayer & Thomasson, 2004).

The difference between seasonal and permanent wetlands goes beyond the amount of water needed during a year to keep them functioning. Further studies in Lower Klamath have found that permanent wetlands tend to be more effective at retaining contaminants over the long run than seasonal wetlands. The refuge as a whole retains around half of the P and N entering it via inflows, as measured by taking measurements of inflow concentrations and outflow measurements at predictable intervals (Mayer, 2005). Formerly, the refuge was hydrologically connected to the Klamath River during spring floods, but is now largely dependent on irrigation return flows to maintain its wetlands – a condition that links the refuge’s ability to support upwards of 1.6 million migrating waterfowl to requirements of agriculture (Mayer, 2005).

2.2 The Idea of Ecosystem Services

Ecosystem services is a relatively new concept, one that seeks to examine the vast array of benefits that society derives from nature. No human activity is possible that does not, in some way, depend on natural processes on at least a very basic level. The continued existence of life on Earth is ultimately due primarily to its receiving electromagnetic energy as a result of fusion in the heart of the Sun, and the age-old natural cycles, phenomena, and processes that have provided tillable soil, accessible and portable sources of energy, and materials. The natural cycles that result in edible crops growing in fertile, hydrated soil are fundamentally important to the accumulation of food surpluses that freed early human civilization to innovate, specialize, and construct an economic system beyond that of subsistence agriculture.

Wetlands are a particularly important ecosystem in large part due to the broad set of important ecosystem services they alone provide. These include water storage, water filtration, nutrient sequestration, habitat, flood control, aquifer recharge, storm mitigation, and support for human recreation and economic production (Mitsch and Gosselink, 2000). Globally, the most important ecosystem services provided by wetlands in terms of their estimated material value to human society are in providing waste treatment, disturbance regulation, and water storage (Costanza et al., 1997). This same piece sought to quantify the global values of ecosystem services across a broad range of categories. The basic premise is that without the services provided naturally by the biosphere, capital systems would collapse and life itself would be impossible (Costanza et al., 1997). Ultimately, all capital is backed by natural processes and systems in the biosphere, without which humanity would never have been able to progress beyond subsistence systems. Ecosystem services aren't as readily valued in markets compared to man-made economic services and capital, but are just as vital (Costanza et al., 1997). As specifically relating to wetlands, Costanza et al. find that globally 4.48 trillion US Dollars (1997) is derived from the services naturally provided by around 330 million hectares of wetlands - an average of $14,785/hectare (Costanza et al., 1997), making wetlands one of the most valuable ecosystems in the world for their area. Their methods have been called into question, but the core logic of estimating the value natural processes and areas provide to human society has become a key component of the contemporary conservation debate.

2.3 Water Storage in Wetlands

Water storage is the primary ecosystem service of wetlands that this work seeks to examine with respect to the Klamath Basin. Lack of water storage is a fundamental problem in the Klamath Basin, where the accelerated loss of its historic wetlands beginning in the postwar period (Campbell et al., 2001) has reduced local annual storage capacity to less water than flows into Klamath Lake in an average water year (Campbell et al., 2001). The availability of water has become a serious conflict vector because of the increased demands placed by human activities on the water supplies of the area, and has led to significant social and political conflict in recent decades (Owen, 2008), particularly during severe droughts when there is insufficient water to meet all demands placed upon it while also ensuring that minimum in-stream flow levels established by the federal government are met (Flug, et al., 2005).

The quantity of water stored in wetlands is primarily a function of two variables: surface area and depth (Grings et al., 2008). Whether a wetland is natural, restored, or constructed, this simple relationship holds. Multiplied together, these metrics provide the volume of water, usually measured either in cubic feet (ft^3), cubic meters (m^3), or acre-feet. This calculation is essentially the same as in calculating the volumetric storage capacity in a reservoir or container. However, there are additional factors that make accurate and consistent estimation of storage volume in wetlands difficult. Wetlands are generally hydrologically connected to other surface waters and groundwater, and typically in equilibrium with these systems (Krasnostein & Oldham, 2008). Water towards the bottom of a wetland percolates into the soil, flowing into groundwater at rates that depend on the nature of the wetland substrate (Shook et al., 2013), including its hydraulic conductivity (Babbar-Sevens et al., 2012), while water on the edges of a wetland may flow into a neighboring stream depending on local conditions.

This dependency on local conditions means that wetlands intended to be used as water storage mechanisms may need to be modified or enhanced in order to increase predictability in their storage patterns (Babbar-Sevens et al., 2012). Levees, dikes, and pumps can help partially isolate wetlands from their immediate surface surroundings, allowing for increased control over their behavior (Babbar-Sevens et al., 2012). Controlling subsurface conditions that connect a wetland to groundwater is a more difficult proposition, but the fact that wetlands tend to exist and persist in an area once underlying soils are saturated (Mitsch and Gosselink, 2000) helps to offset this. In addition, wetland interactions with groundwater are in some ways more easily accounted for, as the water may be available if pumps are utilized or become negligible if the wetland is maintained as such in a permanent fashion, where the underlying soil never dries out and the groundwater recharge losses are more slow and steady.

In fact, even where losses to groundwater are relatively high, this may still bolster the net effect of utilizing wetlands for storage. This is in part due to the local geography, where water eventually drains into the Klamath River, bolstering flows, to the tune of 50% of total return flows observed in the system (Campbell et al., 2001), but also to efforts to pump groundwater to the surface in order to mitigate shortages observed in drought years. Specialized instruments such as radar can even help quantify the amount of water stored under wetlands (Grings et al., 2008). Unfortunately, such a detailed quantitative assessment is beyond the scope of this work, but the groundwater recharge function of wetlands has been documented (Mitsch and Gosselink, 2000) and bolsters any argument for maintaining wetlands in the pursuit of greater water availability in the Klamath Basin.

The third, and generally most significant, factor in understanding wetland water storage is that of evaporation. This process simply involves the upper layers of water being heated by the sun such that they absorb enough energy to vaporize, and enter the atmosphere (Mitsch and Gosselink, 2000). This process can be ameliorated by natural or induced cooler temperatures (Krasnostein & Oldham, 2008), but is a significant limiting factor in long term water storage, particularly in typically broad, shallow storage mechanisms like wetlands, as opposed to the typically deeper storage in reservoirs and lakes. In Klamath, yearly losses to all causes in a permanent wetland are quite often 50% of its initial measured volume, with these losses peaking in July and largely due to evaporation (Mayer & Thomasson, 2004).

In the Klamath Basin, the practical effect of increasing storage capacity, particularly inter-year storage, makes it well worth further investigation. Although in the worst years there is insufficient water in the watershed to meet all needs - if typical in-stream flow minimums are to be met - in most years the limiting factor in water availability, is that of storage. There is presently in the neighborhood of 600 million m^3 of storage in the Upper Klamath Basin, predominantly in Klamath Lake (Flug, et al., 2005). Even in the very worst years Klamath Lake receives more than enough water to be completely filled, such as in 1992 when only 712 million m^3 of water passed through the lake (Flug, et al., 2005). Typically, the Klamath Basin sees twice that or more in a given year, with minimum in-stream flows recommended by Federal Energy Regulatory Commission (FERC) requiring just over 1,000 million m^3 and the net consumptive use for agricultural needs reaching 203 million ft^3 (Flug, et al., 2005). Hence, in most years, and to an extent even in drought years where winter and spring flows may still exceed in-stream needs even as annual demands are far in excess of annual capacity, adding storage would help to mitigate shortages. It has been estimated that storing 25,000 acre-feet (just under 31 million m^3) of water - that is, maintaining a storage reserve over 25,000 acres at an average depth of 1 foot, or 5000 acres at a 5 foot average - would bolster in-stream flows in August by 13 m^3/s (Flug, et al., 2005). This would represent 40% or more of the needed in-stream flows for that month, and could well be enough to support optimal conditions for salmon spawning while having no negative effect on agricultural diversions.

2.4 Additional Wetland Ecosystem Services

In terms of other important ecosystem services provided by wetlands, waste treatment is highly important in the UKB. The waste treatment services of wetlands arise out of their ability to pull particulate matter out of a water column and hold it in the moist soils and vegetation that are present in most wetlands (Mitsch and Gosselink, 2000). Since water is a limiting factor in plant growth, its ready availability in wetland ecosystems allows for plants that grow quickly and absorb contaminants that would otherwise pass on downstream. The mobilized, moist soils in wetlands are typically good holding grounds for contaminants as well. The water supply services of wetlands are fairly obvious, as an acre of wetland covered in water one foot in depth contains, all things equal, an acre-foot of water, which has an explicit market value. Evapotranspiration, percolation into underlying aquifers, and use decreases the stored water (Mitsch and Gosselink, 2000), but after a dry year the value of that stored water may well increase in terms of its usefulness. Habitat is another extremely important service provided by wetlands. Especially in an otherwise dry climate like that in Klamath, nutrition, hydration, and shelter may not be readily available anywhere else. Around the world, wetlands cover only a small percentage of total surface area but are home to a disproportionate number of the world's species (Mitsch and Gosselink, 2000). The recreation services offered by intact wetlands are potentially numerous. Hunting, fishing, birdwatching, and eco-tourism are all important to society, and wetlands can more or less support all at once (Mitsch and Gosselink, 2000). In recent years scholarship has begun to examine the phenomenon of amenity migration, where individuals, families, and even businesses will relocate to an area with inherent amenity provisions (Gosnell & Abrams, 2009), which wetlands can support.

Naturally, not all of the possible wetland service functions are present in all wetlands, and some are more important than others in certain areas. For example, the aquifer recharge service of a coastal wetland may be nonexistent, and likewise an inland wetland may have little to no effect in mitigating a storm's effects (Mitsch and Gosselink, 2000). Isolated, hydrologically disconnected wetlands are likely to play a very small role in flood control, and bio-remediation wetlands that receive significant contamination from heavy metals or other toxic compounds may be completely unsuitable for storing water meant for agricultural use. The configuration of a particular wetland also plays a role in determining its primary ecosystem services; tradeoffs are routinely made when determining the size and depth of constructed or restored wetlands in order to maximize certain services over others (Castro et al., 2011).

Tradeoffs in the ecosystem service provision of a given wetland are due to natural and social influences and needs. Different societies in different places will value one wetland function over another for purely cultural or highly pragmatic reasons (Castro et al., 2011). A community that has recently been affected by severe flooding may be attracted to flood control optimized wetlands rather than those meant to sequester N, for example. Historic connections in certain cultures between wetlands and positive or negative values also influence what sort of wetland will be present in an area (Mitsch and Gosselink, 2000), and thereby determine what its major ecosystem service provisions will be. The level of information and understanding stakeholders in a particular wetland possess is also a key factor in determining what ecosystem services it will be optimized to provide.

Consider the explicit policy in the United States in the early 20th century, which sought to 'reclaim' wetlands for use in what was at the time viewed to be more productive, value added enterprise (Mitsch and Gosselink, 2000). Such policy was made in the view that wetlands were effectively useless swamps, and policymakers were largely ignorant of the services provided by intact wetlands. Only in relative recent years has the "no net loss" policy been adopted, in recognition that wetlands offer value to society as an economic asset when left intact, rather than drained for agricultural use (Hoehn et al., 2003).

So wetlands vary in the ecosystem services they have been naturally or artificially constructed to optimize, both due to their physical characteristics as well as their age. One of the more important variance points in the case of the Klamath wetlands is in the relative sequestration ability of N vs P. The two, at least in their bio-available forms, are significant contaminants introduced into the already eutrophic system, but are not equally sequestered by all wetland types (Hansson et al., 2005). P tends to be more effectively pulled out of the water column by deep wetlands, while N is more effectively removed by broad, shallow wetland bodies (Hansson et al., 2005).

Wetlands that are specifically constructed to intercept and sequester N have actually been observed to increase the quantity of P present in outflows, likely due to the P enriched quality of the underlying soils and the depth of the constructed wetlands (Tanner et al., 2011). Even this dynamic, however, is strongly affected by the age of the wetland in question, the quality of the water entering into it, and the soils that underlay it. Newer wetlands have been observed to export nutrients downstream for a period of time up to a decade after they are first flooded (Ardón et al., 2010). Generally, this increased load on the downstream system peaks in the first few days after flooding, and then gradually recedes until within a few weeks to months the wetland is actively sequestering P and N (Aldous et al., 2005).

This raises the issue of temporal interactions on wetland ecosystem services, at least in the area of nutrient cycling. In the Klamath Basin, where flooding has historically been important in filling wetlands during the wet months, human impacts on the landscape like impoundment and damming have restricted this natural flood cycle. As a result, many wetlands are directly managed: flooded when water is plentiful or when flooding is needed, then drained or allowed to dry out at other times. As a result, nutrient concentrations and the related sequestration is tied to the season, with summer being one of the worse due to the low quantities of water available (Aldous et al., 2005). Initial flood-up events in spring or late summer also increase downstream of loads, often my as much as 16% in terms of P, causing an additional temporal consideration (Aldous et al., 2005).

The quality of the soils and inflows associated with a wetland system also strongly impact the temporal quality of inflows and outflows with respect to nutrient cycling. Nutrients tend to flow towards the reservoir of higher concentration - if the water column in a wetland is saturated in P or N with respect to the underlying soil, then the wetland will tend to sequester these nutrients, and if the reverse is true, the wetland will tend to export nutrients into the outflows (Aldous et al., 2005). In terms of ensuring maximal nutrient retention and filtration services, it is important to keep wetland soils at least moist, if not inundated, year round: this helps to keep equilibrium in the longer term, helping to pull nutrients out of inflows, where concentrations tend to be higher (Aldous et al., 2005, Dunne et al., 2010). There is, naturally, a limit to how much a wetland can due to filter nutrients from inflows as part of the natural services it performs. Over time, wetlands do saturate with respect to nutrients – not to mention carbon, metals, and sediment - they can hold (Aldous et al., 2005). They then need time to let the concentrations decrease via natural processes before they can be relied upon to perform their filtration service.

Klamath is a naturally eutrophic region due to its volcanic soils, which are enriched in minerals, metals, and other potential contaminants. Paleolimnological studies indicate that Klamath has been detectably eutrophic for centuries, but also that Euro-American settlement began a trend towards extreme eutrophication (Graham et al., 2005). This ongoing eutrophic increase is having detrimental effects on the area's ability to support its native wildlife, habitat, and water quality. Bioavailable, reactive nitrogen in particular is dramatically altering the local watershed, largely due to the use of fertilizers containing ammonia and nitrates. Cyanobacteria blooms, low dissolved oxygen, turbidity, and high nutrient concentrations all contribute to a deterioration of the water quality in the basin (Graham et al., 2005).

The remaining wetlands, and even adjacent agricultural fields, are being attacked by an increasing number of invasive species (Jakubowski et al., 2010). Due to the endangered status of two fish species in the area, more and more efforts have been diverted towards the preservation. Unfortunately, trying to manage an ecosystem to save one species inevitably has detrimental effects on the health of other species (Jakubowski et al., 2010). One answer to these growing problems is the expansion of wetlands in the basin. They can sequester around 63% of N coming out of an agricultural field (Tanner et al., 2011), and in some cases as much as 77% (Mayer, 2005). Wetlands can sequester P, especially undamaged wetlands (observed to be about 6-7 times more effective at retaining P (Graham et al., 2005), though the level of effectiveness is a matter of debate, and the range of observed sequestration values is broad (Graham et al., 2005). Regardless, it is likely that the quality of water in the entire Klamath watershed can be improved by increasing the number of wetlands.

2.5 Spatial Aspects of Conservation

The spatial location of wetlands with respect to one another and other ecological or geographic features is of vital importance in understanding the services wetlands provide to adjacent systems and their value in human terms. Intuitively, this can be easily understood using a cartoonish example: the Mississippi River, located as it is in the eastern United States, has negligible physical impact on the Ganges River in India. The two are so far apart from one another that their only relationship takes place in the realm of global processes, and the factors driving such global processes are so strongly influenced by other variables that the two rivers, mighty and vital as they are in their respective continents, are of minor importance. Thus, their lack of physical proximity causes them to be effectively independent systems with respect to one another.

The same principle applies on smaller scales as well. A wetland separated by another wetland by major landforms or long distance can generally thought of as its own entity, rather than a part of the other. However, in a system where hydrologic linkages are observed, such as in a watershed, two wetlands that are many miles apart may be vital to one another on a measurable scale (Soderqvist & Mitsch, 2000). A landscape perspective studies physical and biological interactions between various ecosystems in a geographically linked region, and human presence and structures - social, physical, economic - are all part of a proper landscape perspective (Soderqvist & Mitsch, 2000). In studying both the economic and ecological aspects of a system that covers a great deal of ground, like the Upper Klamath Basin, recognizing that wetlands are linked on a regional scale can be quite helpful in understanding how their value to the area has changed over time.

It is slowly becoming more common to apply an interdisciplinary spatial perspective in looking at natural phenomena, and in an area like the Klamath Basin such a perspective is essential. Especially in a large, complex region like Klamath, wetlands provide services at multiple biological scales: community, population, ecosystem (Soderqvist & Mitsch, 2000). Likewise, they provide services at multiple levels of importance to humans: farms, towns, counties, and entire states derive benefits from wetlands. Even if they only cover a few acres of land in a given area, the combination of numerous such plots do add up - but their benefits are often spread not only within the confines of biological or economic study, but between fields as well. This is becoming more widely recognized in restoration efforts as well as land use planning initiatives, where traditionally biologists and economists would make decisions based on their own discipline-rooted set of priorities, leading to inefficient outcomes (Newburn et al., 1998). The selection of land use priorities that is rooted in interdisciplinary efforts that explicitly recognize tradeoffs between project objectives is therefore of key importance in preserving the maximum function and value in an ecosystem (Newburn et al., 1998).

In terms of assessing the changes in Klamath wetlands that have taken place in recent years, this growing recognition of the need for interdisciplinary understanding of a broader range of tradeoffs than has been traditionally considered is vital. Like most any part of the world where fertile land is a scarce and highly sought after resource, the lands that are developed or used for agriculture are taken from a limited stock of the lands naturally part of the regional ecosystem. This means that the value of a given parcel of land if developed must be weighed against the natural services it provides in order to promote the most efficient outcome for society. Not all land is created equal, and those lands that tend to provide the highest values in their natural state are usually those that are the most sought after for development (Ando et al., 1998). One of the best ways to predict the value of one parcel of land is to discover its spatial proximity to and interconnectedness with an adjacent parcel (Boyd & Simpson, 1999). The growing ubiquity of geographic information systems and the databases that drive them allows for an increased ability to understand these spatial patterns of land value and ecosystem linkages, and promote the most efficient use of a given parcel of land - even a group of adjacent parcels (Humphries et al., 2010). The multiple layers of data that can be included in a GIS database allows for statistical tools to be applied and in depth examination of the relationships between economic and biological variables to take place side by side.

Although this work does not quantitatively address spatial proximity between wetland areas in the UKB, the logic of focusing on areas that have a higher density of wetlands in setting conservation policy follows from the considerations put forth here. Functionally, it is easier to manage a land use system that is simpler in its patterns than one that is more complex, and so simply describing a particular area that is of interest seems reasonable.

Chapter 3 Methods

This work employed two methodological tracks to assess the physical aspects of wetland water storage in the Upper Klamath Basin and the policy ecosystem that governs the viability of enhancing water storage by relying on wetlands. The latter relies on an extensive review of the peer-reviewed literature relating to the typical physical and ecosystem services characteristics of wetlands, and an examination of grey-literature, most notably the Klamath Basin Restoration Agreement, the 2013 Biological Opinion, the United States Department of Agriculture's Natural Resources Conservation Department publications and data with respect to the Wetland Reserve Program and the indispensable book "Water War in the Klamath Basin" by Holly Doremus and A. Dan Tarlock. The former method, intended to physically locate and characterize potential wetlands in UKB, requires a more in-depth description to ensure replicability.

Collecting biophysical or geographic data on a basin scale can be an expensive, time consuming project if undertaken using traditional methods. Remote sensing is in no way a perfect panacea capable of mitigating all such data collection difficulties (Jensen, 2006), as it has its own set of technical hurdles to be surmounted. However, it has distinct advantages that make it a competitive means of collecting data encompassing a broad and growing swath of natural and human studies. Some of these include: simultaneous data collection at physically distant sample sites, repeated visits to a study area that maintain a close to constant set of collection conditions, maintaining the collection conditions over time spans of years to decades, and a relative lack of human-induced random bias introduced at each sample point (Jensen, 2006). Remote sensing also has the advantage of being fairly cost effective (Euliss et al., 2011), primarily because the equipment used has fallen in price over the years, but also because it reduces the cost of paying researchers to physically collect data. Its use has become more widespread as computing and sensing technology has advanced (Finlayson et al., 2009), and is rapidly becoming an indispensable tool in the geoscientist's toolbox.

For this study, remote sensing was selected as the only means of efficiently collecting the data needed to investigate the research question, in large part due to the availability of remote sensing data collected by the same platform going back to 1999. The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) features a 30 m^2 spatial resolution in spectral bands ranging from the visible to the thermal infrared, and collects spectral data over a 185-km swath (Jensen, 2006). Launched in spring of 1999, the sensor has collected data continuously since its inauguration, however, in the spring of 2003, the instrument's scan line corrector failed, which in terms of practical effect means that there are gaps in the data recorded by the sensor. This missing data presents real but surmountable challenges to analysis.

Orbital, passive sensors like Landsat 7 function by converting the energy imparted by photons striking the detection mechanisms to an electric current, which is then recorded as a digital number (Jensen, 2004). The individual detectors only record photons arriving that exhibit particular characteristics in wavelength, allowing data collected from a single area to be broken into spectral bands, such as the blue, green, or red (Jensen, 2004), and the intensity of the signal received at a given point in time.

For the purposes of this research, Landsat 7 ETM+ data were obtained from the United States Geological Survey. Two particular scenes were selected, Path 45 Row 30 and Path 45 Row 31. The scenes chosen were selected due to their together encompassing the majority of the Upper Klamath Basin, and virtually all of it where wetlands are common. A conscious decision was made to exclude a relatively small section in the east of the watershed. The rationale for this was pragmatic, and twofold: first, to reduce the time spent on analyzing a relatively small portion of the watershed that is on the boundary of the Great Basin and quite dry; second, to avoid bias control difficulties that arise from including portions of a different orbital path in the study. While this may exclude some wetlands in the basin, those that are excluded were judged to have a minor impact on the whole system and to be limited in extent. Two images were acquired from each scene during each year of the study, from 2000-2012, in spring (April and May) and summer (August).

The Landsat 7 ETM+ images obtained from USGS were pre-processed to the Level 1T standard, meaning that standard geometric and radiometric corrections were made to the images prior to their being downloaded for the purposes of this work (NASA, 2013). These adjustments to the raw data collected by the Landsat instrument are necessary to compensate for the movement of the sensor over the target landscape and to render the sensor data in a scaled format (NASA, 2013). In addition, they georeference the pixels to actual points on the ground utilizing the Universal Transverse Mercator coordinate system and the WGS-84 projection, and orient the image so that north is located at the top of the final image (NASA, 2013). No other pre-processing was done.

Upon acquiring the images from USGS, the files were processed in the ENVI 4.7 software package. The Row 30 and Row 31 images for the same year were mosaicked together, as they split the study area approximately in half, then cut down in terms of their spatial extent. The manual "region of interest (ROI)" tool in ENVI was used in conjunction with a published map of the basin and Google Earth imagery to manually delineate the portion of the image corresponding with the portion of the basin containing the majority of its water.

To optimally sense wetlands, a subset of the available Landsat bands was chosen based on recommendations in published literature. Landsat bands 1, 2, 3 correspond to the blue, green, and red portions of the electromagnetic spectrum, while band 4 is located in the near infrared, 5 is in the middle infrared, 6 is a longwave infrared band with a different spatial resolution, and 7 is located in the thermal infrared (Jensen, 2006). Baker et al. found that, in addition to being almost as effective at sensing wetlands as higher spatial resolution sensors such as the European SPOT instrument, Landsat bands 2-5 were the best at sensing wetlands (2006). Frohn et al. focused on picking hydrologically isolated wetlands out of crowded landscapes, and found bands 3,4, and 5 to be optimal when used in conjunction with statistical transformations and object oriented classification algorithms (2009).

This research thus chose Landsat bands 3 (Red, 0.63-0.69 µm), 4 (Near Infrared, 0.75-0.90 µm), and 5 (Infrared, 1.55-1.75 µm). The study image areas were subsetted spectrally to exclude the other bands. In terms of the specific spectral response anticipated of these bands to wetlands, UKB wetlands are typically characterized by fairly shallow, nutrient rich waters with significant quantities of emergent vegetation within and around the wetland (Mitsch and Gosselink, 2000). Red wavelength light tends to be absorbed efficiently by vegetation, and also by water, but less so by bare earth. Near infrared light is well absorbed by water and fairly well by bare earth, but plants tend to reflect and emit significant amounts of energy in the NIR portion of the spectrum. The IR portion of the spectrum provides a check on the other bands, allowing false-color RGB images to be constructed that also give a better sense of a particular pixel's spectral characteristics over a wider portion of the spectrum (Jensen, 2006).

To identify wetlands in the study area, a classification methodology known as Iterative Self-Organizing Data Analysis Technique (ISODATA) was employed. Classification systems are generally grouped into two primary categories: supervised and unsupervised classification (Jensen, 2004). The first involves several different methods joined by their common reliance on a human directly training whatever algorithms are later applied to the dataset. This generally involves creating several regions of interest in the image that correspond, as best as the researcher can tell, to particular geographic features of interest (Jensen, 2004). One of several classification algorithms will then be applied that will classify pixels in the image based on the researcher-provided "training." This method has the advantage of using expert knowledge to build a classification system, and can lead to several competing classifications based, for example, on decision trees or statistical analysis.

The second, unsupervised classification, is designed to be a purely hands-off, statistical treatment of a dataset using well-defined algorithms (Jensen, 2004). The researcher modifies the classification result only by changing the parameters of the algorithm, say by altering the number of times the algorithm is run, the weights accorded to particular variables, thresholds for invoking a part of the algorithm, etc. The process is repeatable and self-contained, ensuring high confidence that one classification can be directly compared to another. The primary point where human intervention occurs comes after the algorithm has identified the 'natural' grouping of data points within the image, and involves simply labeling the classes correctly (Jensen, 2004).

Which method to use is up to researcher preferences and the exigencies of the situation. The effectiveness of each is a matter of debate - some researchers argue the virtue of comparable, statistically clean methods, others point out that unsupervised methods without any intelligent constructions are highly inaccurate (Kulawardhana et al., 2013). ISODATA was selected for this work due to its ability to be replicated and customized.

Operating in accordance with specific, user set parameters, ISODATA first creates evenly spaced groupings that together encompass all of the data points in the set, and calculates the mean value of each cluster. It then merges, splits, and otherwise sorts the clusters to reduce the dispersion from the mean inherent in each cluster. The algorithm runs again, shifting the clusters in order to group data into natural classes. The process continues until one of several user set parameters is met (average distant from mean, standard deviations from mean), at which point the algorithm ends, and a map is generated that color codes the pixels in accordance with the classes the algorithm has output (Jensen, 2004).

The specific ISODATA parameter values were arrived at through a process of trial and error, which sought to provide the maximum differentiation between different types of water-filled pixels, but that didn't accidentally pull non-related pixels into a given class by arbitrarily forcing the data to break into more classes than was "natural." For example, when the number of classes was set too high or too low, or the standard deviation allowed was too high or too low, the algorithm gave results that didn't seem true to the real world - pixels in the image located high in the Cascades were classified as 'wetlands' even though it was quite apparent from the unclassified image that this was impossible.

Table 1: Comparison of ISODATA Parameters

ISODATA Parameters Change	Noted Effects
Number of Iterations	Very little differentiation between classes, all water functionally one class, only goes to seven or so iterations
Number of Classes	Decreased number of classes led to obvious, widespread errors of commission. Increasing class numbers (up to 30) allowed differentiation between water types at cost of increased post-classification work
Maximum Class Standard Deviation	Little practical effect unless increased to be very large. Some added differentiation
Minimum Distance Between Classes	Increasing values failed to be helpful, but reducing to one allowed for significant differentiation between water types, the output was more positively responsive to this than any other parameter
Other Parameters	Few to no significant beneficial effects from modifying these

Ultimately, it was determined that the ISODATA parameter that offered the best performance increased the number of potential classes to 30, and decreased the minimum distance between classes to 1. This appears to have allowed the algorithm to split up classes representing pixel groups whose spectral characteristics were dominated by water.

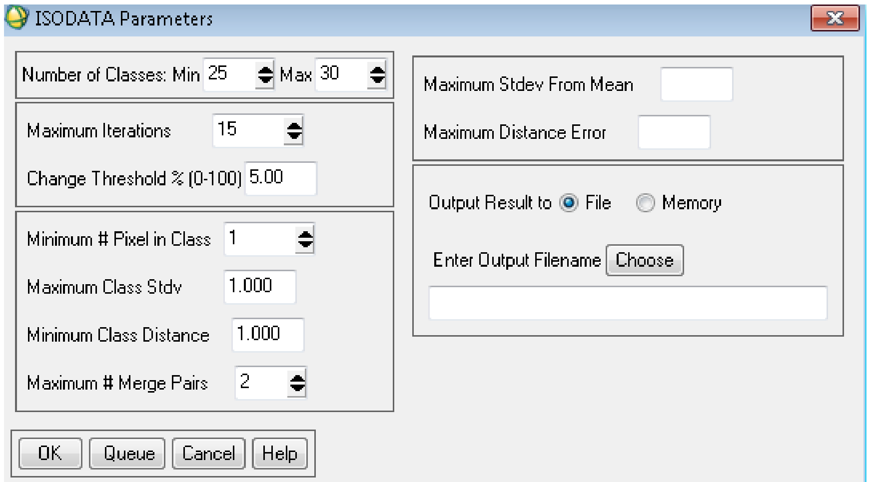

Figure 1: Final ISODATA Parameters

For each of the images in this study, the ISODATA algorithm was applied with the most effective set of common parameters identified. The resulting classified image was then manually assessed alongside the original and a true-color image to identify which classes represented wetlands using reference points in known wetland areas located in the major National Wildlife Refuges. Several years within the study unfortunately had too many clouds affecting the classification to be reliable, and in years where either spring or summer imagery was so affected that year was excluded from the data. Years suffering this fate include 2011, 2008, and 2007. Once each image's wetland classes were identified, inter-year comparisons could be made that estimated the difference in wetland extent in spring and summer.

In summary, the process of acquiring and analyzing the remote sensing data to understand the spatial characteristics of UKB wetlands proceeded in the following manner:

- Obtained pre-processing Level 1T Landsat 7 ETM+ scenes from spring and summer, 2000 to 2012.
- Mosaicked, then spatially (approximate and relevant UKB extent) and spectrally (Bands 3-5) subsetted images.
- Experimented to find effective starting parameters for ISODATA classification that best identified wetlands.
- Applied ISODATA classification utilizing a fixed set of parameters to each image, then manually classified generated classes by examining preclassified, postclassified, and unmodified true color images side by side to identify which ISODATA classes corresponded to reference points in and around the area National Wildlife Refuges.
- Excluded years 2007, 2008, and 2011 from consideration due to cloud cover that seriously hindered classification.
- Compared the difference between spring and summer pixels classed as wetlands to identify 'lost surface water' - areas that flood in spring but dry out in summer and so are most likely to be seasonal wetlands not currently managed to maximize water storage.
- Layered the georeferenced, classified images atop a base image to create a rough georeferenced 'score' map to demonstrate the visually apparent clusters of areas that host wetlands in some or most years.

Chapter 4 Data Analysis and Sources of Error

The image classification methodology described above indicates significant differences in the extent of Klamath Basin surface water between spring and summer seasons. summer months exhibit surface water extents ranging from 67-77% of those identified in spring. An average summer sees around 430,000 pixels identified as wetlands by the ISODATA runs, while an average spring boasts 600,000.

In real surface area terms, this translates to approximately 39,000 hectares (~96,000 acres) for summer and about 54,000 hectares (~133,000 acres) in spring. This is not at all unexpected, and a core assumption (seemingly valid) of this thesis is that more land will be flooded in spring relative to summer, due to the differences in precipitation exhibited between the seasons.

4.1 Identifying Potential Wetland Area

What is of interest is the typical difference between summer and spring - a difference that should identify the area that tends to flood in the wet season, and as such should be more easily used to store water than an area that doesn't flood. This 'typical' difference is then 170,000 pixels, equal to about 15,000 hectares/37,000 acres on average. With surface water extent in both spring and summer stable if not increasing slightly, and the 'typical' or average yearly difference identified, it can be reasonably assumed that UKB typically has a surplus of available water in the early part of the year, present at least in some part of the survey area. The remote sensing classification takes this a step further, and also provides an indication of where the seasonal surface water is located.

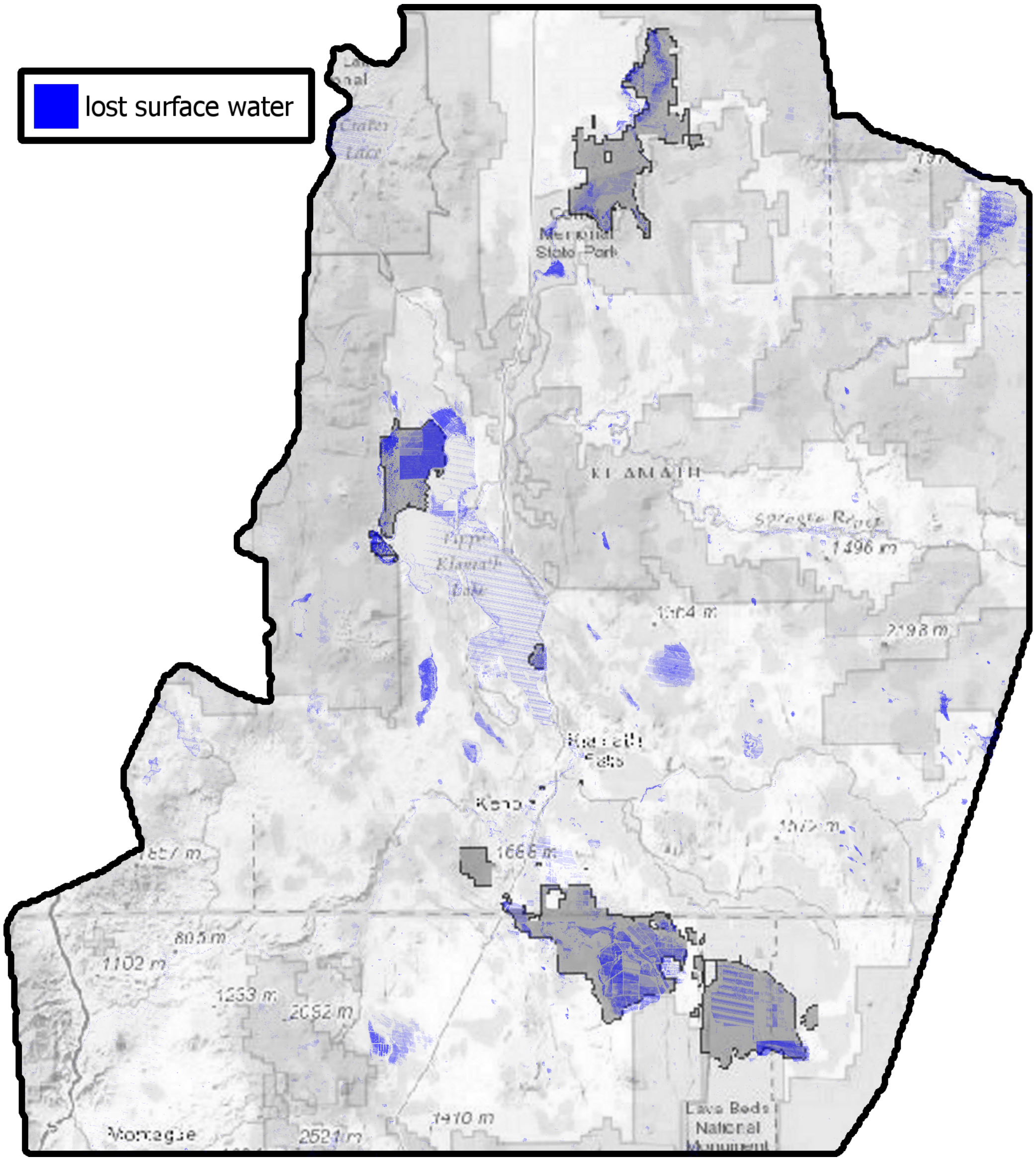

Figure 2: Composite Surface Water Spring-Summer Difference Map
Greater intensity of blue represents location where lost surface waters occurred in more years of the study, hence a better site for storage.

Table 2: Summer Surface Water Extent, 2000-2012 (by class and totals, in pixels)

		2000	2001	2002	2003	2004	2005	2006	2009	2010	2012
Class	First	67,211	69,101	69,001	140,425	125,872	79,440	273,332	85,153	86,071	120,680
	Second	72,376	90,350	48,402	298,363	304,574	311,154	129,515	299,311	330,231	58,912
	Third	275,348	176,455	240,494	43,545	7,569	7,691	66,699	50,409	50,871	267,351
	Fourth	56,238	76,182	78,459		34,017	77,205	76,152	50,108	8,316	32,044
	Fifth	22,847	21,080	31,431							10,518
	Sixth			48,098							20,189
	Seventh										
Crater Lake		-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000
	Totals	**435,020**	**374,168**	**456,885**	**423,333**	**413,032**	**416,490**	**486,698**	**425,981**	**416,489**	**450,694**

Table 3: Spring Surface Water Extent, 2000-2012 (by class and totals, in pixels)

		2000	2001	2002	2003	2004	2005	2006	2009	2010	2012
Class	**First**	10,861	43,621	74,690	112,024	271,451	180,008	287,984	240,308	162,279	142,388
	Second	27,452	104,463	121,579	120,269	276,467	301,513	440,276	257,456	84,583	238,671
	Third	89,072	190,200	191,813	247,667	59,731	118,595	39,008	81,464	294,133	95,539
	Fourth	97,192	152,448	238,450	70,030				58,386		78,211
	Fifth	133,116	99,227	108,757	66,677					73,000	16,494
	Sixth	150,018			18,960						61,609
	Seventh	155,366									88,172
	Eighth										2,792
Crater Lake		-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000	-59,000
	Totals	**604,077**	**530,959**	**676,289**	**576,627**	**548,649**	**541,116**	**708,268**	**578,614**	**554,995**	**664,876**

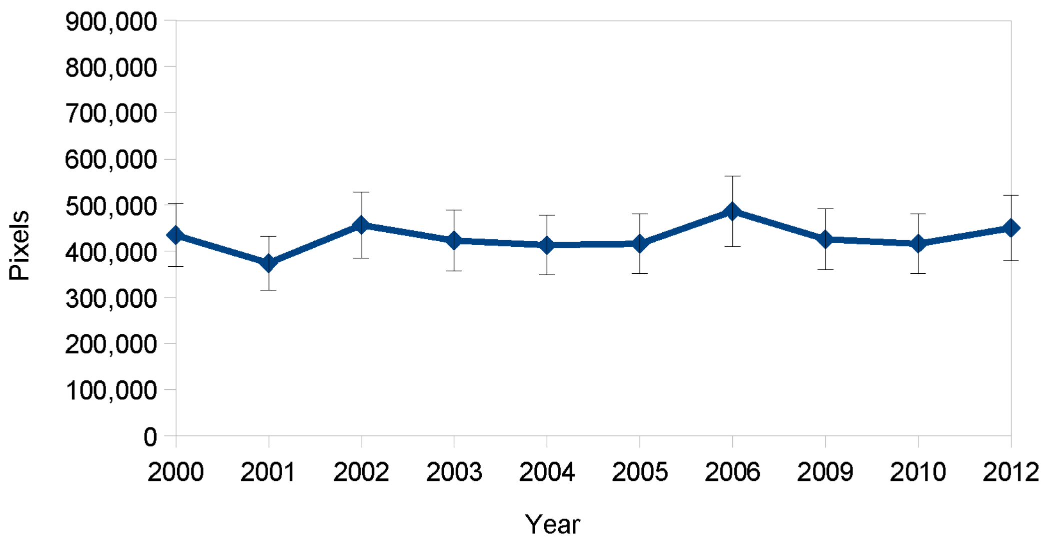

Figure 3: Trend in Summer Surface Water Extent, 2000-2012

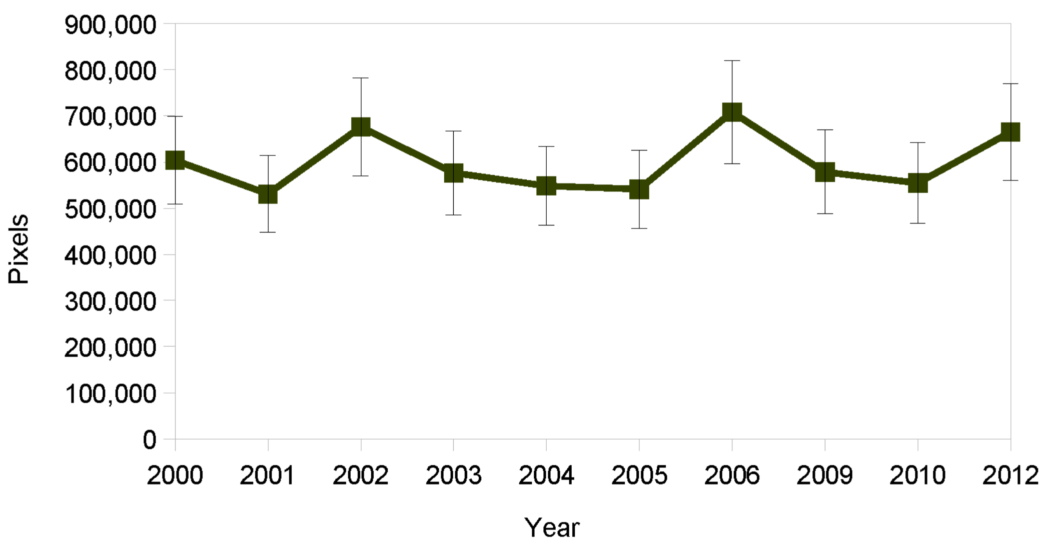

Figure 4: Trend in Spring Surface Water Extent, 2000-2012

Visual inspection of a composite image coupled with a statistical output that together included each year's pixels classified as seasonal surface water yielded four primary areas in UKB in which up to 74% of the total upper basin surface water is located during most years, with uncharacteristically dry years seeing lower values and uncharacteristically wet years seeing higher values. These areas correspond to the three major wildlife refuge complexes in the region: Upper Klamath, Lower Klamath, and Klamath Marsh, with additional concentrations of seasonal surface water present at Sycan Marsh, various shallow lakes, and also in relatively smaller quantities around Meiss Lake and Tule Lake, the former partially protected as a state wildlife area.

What this means is that the Klamath Basin typically holds around 37,000 acres of seasonal surface water areas, which exhibit a tendency to flood in spring and retain water for some time, before drying out in fall. Most of these are located in and immediately around major wildlife refuges. Given that areas shown up in satellite imagery as being wet in spring but dry in summer can be estimated to have hyrophilic soils, and so meet a key criterion for recognition as a wetland, it seems reasonable to believe that there lies, in UKB, the potential for 30,000 acres to be dedicated to water storage in and around lands that are predominantly public and naturally suited to storing water.

4.2 Estimating Water Availability

To assess the volumetric aspects of water patterns in UKB, published gauge data were obtained from the USGS that indicates the average volume of water passing out of

Iron Gate Dam at the southwest edge of UKB in a given month and year. This data were essential to the project for two reasons.

First, determining potential storage area in seasonal wetlands only offers up two dimensions key to identifying the total storage available - depth is just as critical. 1,000 acres of wetlands covered in 1 foot of standing water results in 1,000 acre-feet of storage, but those same acres covered in 5 feet of standing water results in 5,000 acre-feet, and has the advantage of being a more efficient storage mechanism as the same surface area as in the smaller depth example is exposed to evaporation, almost the same area is exposed to percolation through the soil, and yet there is more water between the evaporation and percolation zones that will remain largely untouched by such losses.

Second, although the water shortages in UKB are predominantly seasonal, with plenty of water available to meet all demands through the spring but insufficient supplies available to cover summer, taking the water to be stored in seasonal wetlands must still be arranged so that ongoing needs are not ignored. For example, diverting all the water for several days in March might fill the wetlands to capacity, but cause the Klamath River to temporarily dry up, which would be lethal for fish and violate the water rights of downstream users.

The gauge data, expressed in average volume/second in a given month, allows for raw data speaking to the historic patterns of water availability to be discerned that directly impacts the supply of water available in spring to be stored away as a buffer against summer shortages. Due to requirements to maintain certain in-stream flows at all times, only those flows above and beyond this floor can be used to maintain seasonal wetlands into the summer.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	2,147.0	3,045.0	3,126.0	1,962.0	1,781.0	966.8	685.2	671.6	783.3	963.5	871.4	906.7
2001	925.6	877.5	892.2	1,222.0	1,444.0	1,589.0	713.4	659.4	683.0	928.0	888.3	830.9
2002	1,162.0	1,465.0	1,704.0	1,170.0	1,009.0	620.5	511.8	379.7	472.2	668.2	493.1	575.6
2003	695.2	557.8	1,077.0	1,979.0	1,742.0	893.5	623.1	675.3	891.3	934.2	1,046.0	1,130.0
2004	802.9	1,186.0	1,285.0	1,202.0	850.6	594.7	347.8	429.8	545.3	432.1	648.6	643.2
2005	581.4	405.1	417.7	899.2	2,794.0	861.8	623.6	686.5	828.1	1,013.0	911.6	1,461.0
2006	4,894.0	3,509.0	2,843.0	5,328.0	3,119.0	2,643.0	893.8	548.9	714.8	872.4	923.3	835.7
2007	873.4	1,093.0	2,384.0	1,540.0	959.3	1,154.0	755.0	704.2	679.2	853.6	922.1	929.6
2008	876.5	975.0	1,404.0	2,095.0	1,364.0	1,403.0	756.6	740.7	746.3	919.1	927.4	953.0
2009	842.6	831.7	994.7	989.0	923.9	1,118.0	821.5	742.7	684.9	932.3	964.1	1,027.0
2010	954.7	909.5	1,049.0	929.9	761.7	651.7	583.9	755.7	761.3	738.5	1,077.0	822.6
2011	874.7	1,491.0	2,101.0	3,006.0	2,501.0	1,837.0	855.3	767.5	844.2	700.9	1,060.0	871.8
2012	878.4	603.4	785.2	2,465.0	2,105.0	1,175.0	820.6	762.1	813.4	813.4	813.4	813.4
Average	1,269.9	1,303.8	1,543.3	1,906.7	1,642.7	1,192.9	691.7	655.7	726.7	828.4	888.2	907.7
Minimum	581.4	405.1	417.7	899.2	761.7	594.7	347.8	379.7	472.2	432.1	493.1	575.6
Variance	1,153.2	937.1	834.3	1,215.3	784.8	574.1	153.1	126.2	118.0	158.7	163.2	220.1

Table 4: USGS Gauge Data at Keno, Oregon, along Klamath River, Jan-Dec 2000-2012
USGS Gauge at Keno, Oregon, obtained 2013

In typical years, Gauge data since 2000 obtained at Keno, Oregon - a site not far below Klamath Lake - indicates that April and May typically see flows in the range of 1600 - 1900 ft^3/s. Keeping to minimum flow recommendations of nearly 1200 ft^3/s on average in April and May as offered by the Federal Energy Regulatory Commission (FERC), still results in more than 500 ft^3/s of water moving down the Klamath River at Keno that could quite conceivably be removed from the river and stored against dry summer conditions. This scenario would result in the availability swelling to nearly 60,000 acre-feet of water, which could fill 30,000 acres of seasonal wetlands to an average depth of 2 feet.

4.3 Practical Effects of Utilizing Area and Volume for Storage

An average sequestration of 500 ft^3/s during these months, even assuming a fairly pessimistic 50% loss of stored water to evaporation and absorption in the soil over the subsequent months, would allow in-stream flows to be boosted 250 ft^3/s throughout July and August, which would represent about a 40% increase over average year flows measured between 2000-2012, and upwards of a 70% increase over minimum observed flows in the worst of these years, 2002. Alternatively expressed in agricultural terms, given a typical use of about 2.1 acre-feet of water to irrigate one acre of farmland and assuming the same level of losses, 15,000 acres of farmland - around 8-9% of the total farmland supported by the Klamath Reclamation Project - could be supported without impacting in-stream flows above and beyond what could be supplied without this additional storage capacity. If this were managed such that the return flows from post-irrigation runoff were added back into the water budget, (in effect, counting only net consumptive flows against the water allocation budget) then this figure could be boosted by about 40%.

Drought years would still pose a serious problem, however, if adherence to high in-stream flows during spring is mandated. In bad years, April/May flows have been observed to decrease to as low as 760 ft^3/s, with an average minimum flow between the two months of about 800 ft^3/s. If for these years we can relax the requirement to follow recommended in-stream flows for spring, and instead use the minimum of just over 700 ft^3/s minimum recommended for summer months by FERC, a net difference of 100 ft^3/s

for two months can result in 12,000 acre-feet of water being stored, enough to boost summer flows by 50 ft^3/s or irrigate 1200 hectares of farmland even in a very bad year.

If assumptions were further shifted, and excess water above the FERC summer minimum were stored beginning in January of a given calendar year, gauge data for the 2000-2012 period indicates that an average around 200 ft^3/s of water above FERC summer minimums could be extracted and stored even in the very worst of years. By gradually filling storage sites earlier in the year, even in this case enough water could be obtained to equal the more optimistic wet spring plus April and May collection period totals of 60,000 acre-feet of water that could be stored. Using this technique, the average flow rate measured across the entire January - May period from 2000-2012 (excepting one very wet year - 2006 - that skews calculations significantly), and restoring the assumption of following mandated FERC minimum flows of 1200 ft^3/s throughout these seasons, a net available quantity of 100 ft^3/s is available, on average, for storage. This fairly conservative estimate still results in 30,000 acre-feet of water available to be taken and stored.

Ultimately, this analysis that couples the spatial area exhibiting a strong affinity for flooding and the recent history of the volume of excess, unused water that passes through the watershed results in a decent range of estimates for the amount of water that could be stored and approximately where such storage would be located. In general, between 12,000 and 60,000 acre-feet of water could be readily stored on 20,000 to 30,000 acres in UKB that are most likely to be natural, seasonal wetlands, and located in or near public lands. These levels of water storage have practical significance for the basin as a whole, as summer in-stream flows could be boosted anywhere from 50 to 250 ft^3/s, or 1200-6000 hectares (1.7%-8.5% of Klamath Reclamation Project totals) of farmland could receive irrigation water, or a combined allocation that partially irrigates, and partly boosts flows, could be agreed upon.

4.4 Uncertainty and Error Analysis

There are, of course, several sources of error that must be identified and examined in this analysis. First, the classification scheme could be flawed. With parameters being set by the user and mechanics taking place in a 'black box' it is difficult to know for certain what sort of random or systematic errors may creep into the ISODATA runs. The classification scheme in this respect stands or falls with the general strength of ISODATA itself.

To estimate the reliability of the ISODATA algorithm, two experiments were conducted to verify the extent of the variation that can be expected from altering the starting values and in the natural variation of the algorithm when working through the same data multiple times with the same starting values.

The first varied the number of pixels falling into wetland categories when the most responsive parameter, minimum distance between classes, was allowed to vary from the default value of 5 to 1. Significant changes were seen in the first few iterations, as minimum distance decreased to 3, but fewer were observed as this changed from 3 to 1. The total variability in changing from 3 to 1 came to about 8.6%, and this was taken to be the maximum error rate (both errors of commission and omission) associated with altering minimum distance between class values.

The second experiment varied the number of pixels falling into wetland categories when the second most responsive parameter, number of classes, was allowed to vary from the default value of 10 upwards to 20 and 30. As with minimum distance variability, the variability due to number of classes was initially significant - as the value increased from 10 through 20 - then began to decrease. Above 30 changes were notable, but attempting to manually classify this number of classes proved extremely time consuming, and so the 30 classes mark was accepted as a reasonable stopping point, with the error variability reaching 6.1% of total pixels.

Perhaps even more likely are researcher generated errors that result in the necessarily manual process of identifying what the classes ISODATA put forth actually mean in the real world. Without the time and funds needed to physically ground-truth the results of the algorithm, there is no way to be absolutely certain of the error levels in the assessment. The method used here to tailor the algorithm output to real-world conditions was to examine pre and post processing versions of the image, in conjunction with published maps of the study area, to intuit the correct classification-real world link. At times, even this is not enough - in one particular year, 2010, the spring classification included a class of spectrally similar pixels that clearly contained errors with respect to the real world. Clouds, shadows, and other transient issues combined to ensure that a large borderline class that clearly contained a large quantity of wetlands could neither be included as a whole or excised entirely. The decision was made to apply a simple correction, reducing the class size in the analysis by 50%, to account for this.

Precautions were taken to mitigate user-induced error. First, the post-classification identification of the entire ISODATA output was done several times and with significant time gaps between each operation, to ensure that each class appeared correctly identified as representing surface waters after several 'looks.' Second, as close to a systematic process as possible was employed, that identified several broad meta-categories of classifications, that appeared to be common in each ISODATA treatment of each scene. For example, Crater Lake and several other mountain lakes typically appeared in the same class post-ISODATA. Likewise, much of Klamath Lake and other shallow water bodies appeared in the same class. Such similarities were used to help judge, on a case by case basis, whether a particular class included significant bodies of water, or not. Finally, a basic regression output with August pixels as the dependent variable and spring pixels as the independent variable, paired together in their particular years, was run after each classification attempt to identify the R^2 value that broadly measures the 'fit' of a model (Wooldridge, 2012). When a class was included or removed from the meta-class of 'surface water' in one season or year, similar classes were removed as well. The totality of the change was examined via the regression output to determine the change in R^2 for the 'model' as a whole. Assuming that spring and summer surface water extent should be very closely linked - especially because, at this point, permanent surface waters had not been subtracted from the imagery - this is thought to have helped standardize the post-classification process and helped to minimize non-systematic user error.

The nature of remote sensing itself was also a source of error, and one that inevitably impacts each and every image, though hopefully in approximately the same manner. First, clouds are sources of serious random error, as they appear in different places in each image and significantly alter apparent spectral characteristics of nearby pixels. To minimize their effect, years with significant cloud cover over the study area were excluded - 2007, 2008, and 2011 all suffered this fate. Second, the mechanical failure affecting Landsat 7's scan line corrector causes significant striping in all post-spring 2003 images. These are present in the same quantity in all images, though their location changes slightly, complicating interpretation of classifications.

Scan line corrector problems impact the results as the process of computing difference maps from the same-year spring and summer imagery collapsed the classification into three classes for each image: 0, for no data; 1, for wetland; 2, for not wetland. To identify seasonal wetlands, the difference map compared pixel extents in each collapsed class. The number of spring class 1 pixels minus the number of summer class 1 pixels equalled the difference, and so the seasonal wetland value. The scan line corrector problem effectively means greater number of 0 value pixels in both images, causing errors of omission - actual wetland pixels are missed - that by the comparison of spring to summer results are translated to errors of commission - wetland pixels are assumed to exist where they actually do not.

Fortunately the scan line corrector induced errors were canceled out during the course of the work by simply subtracting any wetland 'gains' - a movement from class 0 to 1, as movement from 2 to 1 is highly unlikely given the hydrodynamics of the area -

from the total number of wetland losses: movement from class 1 to 0 or 2. Because the scan line striping does not affect the same pixels in each image, is proportional from image to image, affects only 3% of pixels where most surface waters in UKB are, 72% of surface water pixels present in spring typically do not disappear in summer, and 'gain' of wetlands seen in the difference map should most likely represent surface waters that never changed (ie, were errors of omission in spring) and so should be added to the spring number of pixels in class 1. This should have offset whatever errors of commission were caused by the scan line corrector induced striping in the summer side of the difference map, leading to less than 1% rate total error of omission. This is borne out by the lack of a major change in extent of wetland pixels identified in the pre and post scan line corrector failure classifications and difference maps.

There are systematic methods of mitigating scan line corrector errors, such as the forward and inverse Fourier transforms coupled with Minimum Noise Fraction techniques (Jensen, 2006), that seek to identify persistent sources of 'noise' and excise it from the imagery (and hence and later classifications) but they are ultimately statistical in nature, and can only estimate the 'correct' value for an affected pixel, not provide the 'true' estimate. As such, although it results in a loss of area attributed to surface waters/seasonal wetlands, it was chosen to allow these systematic errors to persist to avoid drawing false conclusions, no matter how statistically reasonable. A side effect of this is that, on the whole, the area estimates presented here should actually under-estimate the true quantity of potential seasonal wetlands in the UKB.

The total error introduced by the remote sensing classification process is judged to be 15.7%, resulting in an overall accuracy of 84.3%. This maximum error is reflected in the error bars in figures 2 and 3.

Moving from remote sensing/image classification error to the errors implicit in the assessment of the gauge data, the first and most significant issue is that of spatial complexity. Gauge data were collected from USGS measurements at two sites: Keno, and Iron Gate Dam. Keno is upstream, not far from Klamath Lake itself, and so its data were used rather than Iron Gate's, which is further downstream in northern California. Still, even choosing a data collection site so close to Klamath Lake assumes a lack of spatial restrictions that are not realistic, but necessary to keep the scope of this thesis reasonable.

In particular, only total quantities of water available in the watershed are considered, not the difficulty - or impossibility - of delivering such water over long distances or upstream. Without potentially expensive pumping mechanisms, water that is measured passing through Keno cannot be removed for use in fields near Klamath Lake. The location where water enters the main branch of the Klamath River will determine its usability and the value of storing it for agricultural purposes. Actual management of the region's water supply may invoke significant limitations on how much water can actually be stored, say, north of Klamath Lake: maintaining sufficient in-stream flows at the mouth of the river is of little use if vital tributaries are dried up in the process of diverting water for storage. Further research into practical management of any attempt to store water on a large scale would need to be done to identify practical and economically optimal storage locations.

The minimum flow requirements presented here are quite basic, and taken directly from the literature. However, there is clearly a significant debate underway on the actual minimum flow standards that should be set to ensure the health of downstream species. Some entities, like FERC, advocate for one standard, while others, for example the National Marine Fisheries Service (NMFS), use a different standard. Politics surely plays a role here, but in large part recommendations emanating from any particular agency need to reflect the primary concerns of that agency. FERC may be only concerned with ensuring adequate and consistent hydropower feedstock, while NMFS is concerned with maximizing the population of salmon spawning in the various tributaries of the Klamath. No fully authoritative voice has emerged to settle the debate, nor can one be expected to do so, although the growing trend is to accept the more stringent NMFS requirements as the mandated minimum in stream flows (Mayer, Personal Communication, 2013).

Chapter 5 Discussion

Although errors in the data collection and analysis portions of this project are certain to play some role, the estimates presented above of up to 60,000 acre-feet of storage potential - depending on how wet of a winter was experienced - in the portion of Upper Klamath Basin located inside and proximate to the major wildlife refuges appear reasonable. Given that this is a sufficiently robust result, and practically significant if we assume typical agricultural revenues are approximately $560 per irrigated acre (Burke et al., 2004) - thus resulting in protected agricultural revenues in drought years running into the millions of dollars - what remains is to connect the physical possibilities presented by water storage in wetlands to a reasonable policy initiative capable of producing a socially beneficial outcome.

5.1 Coupling Analysis to Policy

Understanding the connections between science and policy is increasingly being viewed as a key element in realizing the potential benefits of harnessing the natural world for social purposes (NRC, 2012). All too often, differing culture and the technical use of language stand between harmonizing the spheres of scientific analysis to effective public policy. While it can be challenging to coordinate collaboration even between engineers from different disciplines, achieving the same between engineers and social scientists is an endeavor fraught with potentially crippling barriers. And yet, it must be successfully attempted in order to derive the greatest benefit from the research activities in both science and social science.

It has been demonstrated that the Upper Klamath Basin suffers from a shortfall of storage (Campbell et al., 2001, Flug et al., 2005), resulting in insufficient retention of water to meet all the demands placed upon it even in a relatively wet year. In a drought, the situation is far worse - and yet, even in the worst local drought year of the past half century - 1992 - which saw less than half the normal flows in UKB there was insufficient storage to contain just the water flowing through Klamath Lake (Campbell et al., 2001).

The data analysis conducted in this work shows that a significant opportunity exists to make use of areas that naturally exist as seasonal wetlands as shallow storage systems, which would be used to increase the overall storage in the basin. Approximately

37,000 acres of seasonal wetlands typically occur each year in the Upper Klamath Basin, even in relatively dry years, with more than 30,000 acres occurring in or proximate to the major wildlife refuges in Upper Klamath, Lower Klamath, and Klamath Marsh as well as Sycan Marsh, Tule Lake, and Meiss Lake. Using the FERC recommended minimum in-stream flows, in most years up to 60,000 acre-feet of water can be easily pulled from the Klamath River and its tributaries in the January-May time frame and placed in areas that typically flood naturally, and so can be assumed to be more suited to storing water than other places. If this were to be the volume stored at the start of June in an average year, assuming no withdrawals for other uses, typical evaporation rates would result in 30,000 acre-feet of water remaining in these areas by around October, when precipitation would begin to offset evaporation losses and then begin replenishment.

This means that between June and October at least 30,000 acre-feet of water would be available for withdrawal as needed, or be a near-guaranteed level of inter-year storage available the next year if a drought struck. This equates to over 37 million ft^3 of water, an over 6% increase over the current baseline storage capacity of the basin.

Considering the Klamath Basin as a cohesive system, where water stored and then released into the Klamath River or its tributaries effectively offsets the need to reduce an equivalent volume used for irrigation, seems sensible given the relatively zero-sum nature of water competition between irrigators and conservation. If published estimates of 2.1 acre-feet of water per irrigated acre (Flug & Campbell, 2005) hold, and approximately $563 in revenues are earned per acre irrigated in the basin (Burke et al., 2004), 30,000 acre-feet of water that is annually available to the system can safeguard over $8 million in agricultural revenues on just under 15,000 acres in a drought year, where otherwise irrigation diversions would have to have been shut off due to lack of availability and the seniority of other rights, including tribal and federal government claims.

Another way to look at the potential value of this storage would be to examine the estimated prices paid under a water bank system, where estimates are that a $73 price offered to water suppliers willing to forgo their usual water right in a given year would result in 30,000 acre-feet of water being offered for sale (Burke et al., 2004). This corresponds to nearly $2.2 million for a year. In a sense, were this increased storage capacity used as part of a water bank, it could theoretically purchase enough water to fund almost four times its value in cropping revenues, ostensibly by shifting water use from marginal to more productive agricultural lands, improving efficiency of use within the basin.

One way or another, increasing net effective storage by 30,000 acre-feet would be a boon to the basin even in purely business terms. While it is beyond the scope of this work to precisely estimate the non-market value of the ecosystem services provided by wetlands in UKB, it is virtually certain that they provide a set of spillover benefits that will accrue to the region as a whole. So long as management of wetlands for this purpose is not ecologically damaging on the whole, and profitable from a business perspective, it seems reasonable to assume that it would be a worthwhile initiative.

From a scientific perspective, increasing storage capacity by restoring and managing wetlands explicitly to maximize their ability to provide this service appears to be feasible given the past history of flows and timing, of the typical physical extent of wetlands and their location. And from a policy perspective, there appear to be clear merits to a management scheme that uses wetlands explicitly for this purpose, in order to help take advantage of the full year's precipitation patterns and use them in a manner conducive to maximum social benefit.

What remains, then, is to assess the options and the challenges that would inevitably face any policy that affected management of water and land in the area for this purpose. There are manifold political and cultural factors that strongly influence the potential for any change in policy in the Klamath Basin, not least of which is the ongoing collision between stakeholders who each provide unique services to local society - irrigators to the economy, tribes to the continuity of human history and culture, regulators to protecting the increasingly fragile ecology of the area's flora and fauna - and who each require an allotment of water to succeed in their individual goals. The Klamath Basin's struggle for water has been characterized as a 'water war' (Doremus & Tarlock, 2008), and suggesting any change whatsoever is to risk running afoul of any of these influential and important interest groups. But an initiative that holds the promise of benefiting each major group in roughly equal equal measure would seem to have the greatest chance of meeting with the hope of gaining a hearing and reasonable consideration.

With tribes largely owning rights to in-stream water, and having seniority in these rights recognized by law (Gosnell & Kelly, 2010), the irrigators and regulators are the focus of attention with respect to a management scheme to store water in seasonal wetlands explicitly managed for this purpose. This work turns now to a discussion of the issues involved in managing lands under the purview of each group, assessing their unique requirements and the potential benefits each would stand to gain by participation in their respective proposed policy regime.

5.2 Management Considerations for Storage on Public Lands

Public lands comprise at least half, if not the bulk, of those lands that appear in the satellite imagery to routinely exist as seasonal wetlands, even in relatively dry years. These are largely located in existing Upper Klamath Basin wildlife refuges - Upper Klamath, Lower Klamath, and Klamath Marsh. There is additional storage potential located near Sycan Marsh,Tule Lake and Meiss Lake, each of which are host to a lesser but still potentially important quantity of viable wetlands. All told, of the 37,000 acres identified by the Landsat Data as typically existing in the basin in a seasonal capacity, 1/2 to 2/3 are almost always in and proximate to these refuges - with the greater proportion occurring in dry years, enhancing these areas as focal points for a new management regime.

Currently, these lands hold water rights that are effectively junior to those of all other users in the basin, and are almost completely reliant on agricultural return flows beginning in August to fulfill one of their primary functions, providing habitat for migratory waterfowl in autumn (Doremus & Tarlock, 2008, Mayer 2004). Due to this, in dry years there may be little to no water available, with resulting predictably detrimental impacts on the ducks and geese that have traditionally relied on the Klamath Basin to rest and feed on their way to wintering grounds in the California Central Valley and beyond (Craig & Takekawa, 1996).

And yet, even when autumn water availability is low, by May of the following year these refuges are typically flush with water. This may simply be because they are the last remnants of the floodplain traditionally dominant in this season in the basin (Doremus & Tarlock, 2008). The satellite imagery clearly demonstrates these regions as a focal point for spring water which is derived from snowmelt and precipitation, although they ultimately lose this water and go dry by August unless management intervention holds the waters in place. This is likely due to the strong interplay between the generally predictable total of volume of water passing through the basin during the predictably wet months and the lack of storage capacity currently available.

This seasonality and the relative ease with which these lands flood when water is available offers a prime opportunity for enacting a management scheme dedicated to storing water. Rather than letting the water entering into these wetlands run its natural course, slowly flowing out into the rest of the watershed once external water levels drop below those in the wetland proper as happens in a natural seasonal wetland system (Roseberg, Personal Communication, 2013), the existing infrastructure of levees and pumps present in the wildlife refuge system can be manipulated to hold back and store as much water as possible in the months when it is plentiful. A levee system can hold water up to the maximum height of the lowest levee, and such structures are extensive in UKB, easily noted by cursory visual examination of even fairly low-resolution satellite data.

With fall and winter rains naturally saturating these soils, as much water in the form of spring precipitation and snowmelt as possible can be diverted into these wetlands, until they are ideally at their maximum capacity. At the point where demands for water exceed the excess capable of being diverted to the wetlands, these diversions can cease. Over the warm summer months and up until fall, there will be losses of up to 50% of the total starting volume (Mayer, 2005), but arguably 50% of something is still better than nothing. In autumn, as the rains begin again and agricultural return flows become available, water can again flow into these wetlands to begin the refill process.

The key element here is actively managing what are currently seasonal wetlands as permanent wetlands. In all, the losses during the course of a year are similar between seasonal and permanent wetlands, with seasonal wetlands seeing the majority of their loss in the flood-up phase (Mayer, 2005). However, this dynamic ensures that even in terms of multi-year storage capacity permanent wetlands have a distinct advantage. During a single water year each class of wetland will use approximately the same quantity of water, but in the following water year the permanent wetland, so long as it does not dry out entirely, will logically not require an allotment of water to re-saturate underlying soils. This means that less water will be needed to achieve maximum water levels by the following summer, with the balance that would have gone into soil saturation effectively being available for use later in the year - a hedge against a drought.

In effect, while a seasonal wetland is good at providing a high quantity of water at a distinct time of the year in the Klamath Basin - June - a managed, permanent wetland can provide a similar total quantity of water spread out over a longer time period. This reduces the amount of agricultural return flows needed to ensure waterfowl habitat is available during the fall migration, and provides a basis for inter-year storage so long as the wetlands are not allowed to go dry save in a drought year.

However, there could be challenges to a public land wetland water storage regime, as the refuges have traditionally hosted agricultural operations during the months when waterfowl are not present, with grain crops are grown on the fertile seasonal wetland tracts and harvested prior to the autumn flood-up (Doremus & Tarlock, 2008). This practice of leasing lands to farmers during the time of year when waterfowl are not intensively migrating through the basin poses a significant barrier to the institution of a storage regime in the refuges (Doremus & Tarlock, 2008). This is due both to the natural interest of lessee farmers to continue with business as usual and that of the federal agency in generating revenues via the leasing process. Dedicating area on these refuges to storage would be most efficient if the same location was flooded each year, allowing effective multi-year storage. While farmers elsewhere in the basin would benefit from the general increase in irrigation waters available in drier years, those specific farmers who rely on land leases in the refuges would suffer from, and be likely to oppose, this land use decision (Doremus & Tarlock, 2008).

5.3 Management Considerations for Storage on Private Lands

Initiating reliable water storage on private lands is a trickier proposition than doing the same on public lands, because absent a predictably unpopular move to force idling of agricultural land and the construction of storage infrastructure, voluntary participation must be relied upon to achieve the desired effects. Although significant work has examined establishing market based systems, such as water banks (Burke et al., 2004), to help smooth supply issues during dry years, such systems rely only on basin-wide optimization of incentives and opportunities. They do not alter the underlying dynamic of too little water for too many users during seasonal and annual droughts. Additionally, the standard rational choice assumptions necessary for effective economic modeling do not necessarily hold in the Klamath Basin, where history and culture have invested strong social bonds and values that do not conform to cold rational logic (Doremus & Tarlock, 2008).

Economic incentives do play a key role in the behavior of individual farmers, to be sure - they simply aren't the only forces at play. To achieve an effective stimulus for storing water on private lands, attention to incentives must be paid. Farmers, even though they may have significant emotional ties to the land and their employment (Doremus & Tarlock, 2008), must still to some extent make rational economic decisions, or face financial ruin. Their lands are their primary economic engine, and they logically farm them in the hopes of paying their own costs, and ultimately turning a profit.

A partial solution to the problem of incentives has been presented over the past few decades in a successive series of federal Farm Bills, which have authorized federal funds to pay farmers the bare land rental price - self reported as part of a bidding process - to allow a long term return of the land to a more natural state (USDA, 2013). Administered by the US Department of Agriculture (USDA), these conservation easements, particularly the Wetlands Reserve Program (WRP) which is similar in design but more focused on a particular area of conservation than its cousin, the Conservation Reserve Program (CRP), enables farmers to avoid the risks of cropping and simply receive a payment for the use of their land for an agreed upon period of time (USDA, 2013). The system is voluntary and impermanent, so farmers are not compelled to forever give up their rights to dispose of their land as they wish. They cannot crop their lands - but also forgo the cost of doing so and the risk of crop loss, which affects approximately one-third of Klamath Basin farmers at an average of $20,000 per underwater operation (Doremus & Tarlock, 2008).

The WRP offers the possibility of establishing a set of lands for a clear period of time that will be available for use as wetlands (USDA, 2013). Such wetlands can technically be flooded to a reasonable depth in order to store water, and managed such that they hold these waters back save when it is needed elsewhere. The WRP precludes cropping operations or operations that degrade the wetlands, but not making use of the ecosystem services provided in a financially positive manner (USDA, 2013). It does not appear at all against the spirit or letter of the program regulations to allow for WRP enrolled lands to be heavily flooded when water is available, then lose water when it is needed elsewhere.

Enrolling lands in the WRP does not, of course, offset the potential gains a landowner may realize from intensive farming operations in good years. This lack of an upside provides a threat to the broad acceptance, in rational terms, of a private land water storage initiative that utilized the WRP to pay landowners for the bare land value of their property. To further provide incentives for participation in the program, and boost the number of willing landowners who can provide storage for water, it is necessary to find some means of compensating them further.

A water bank has been initiated in the Klamath Basin (Burke et al., 2004), but up until now has relied on merely transferring water rights from one holder to another in exchange for payment (Doremus & Tarlock, 2008). A policy program that takes advantage of the WRP to offer payment to participating landowners would be well served if it also incorporated the water bank system, allowing farmers who enroll in the WRP to gain a financial return from the sale of water stored on their land during wet years. In effect, participation in both the WRP and water bank would give farmers an opportunity to earn income on top of payments received for the use of their lands in a conservation effort, while not adversely affecting the performance of these lands as conserved areas.

Such an effort would likely not fully compensate farmers for the gains they may realize in a good year of farming. Although the average gross revenue per acre in the Klamath Basin is approximately $563 (Doremus & Tarlock, 2008, Burke et al., 2004), the estimated price for water rights under the existing water bank system has been estimated to be in the $70-$75 range (Burke et al., 2004). Consider, however, that net revenues will almost certainly be far smaller than the gross - net is around 1/3 of gross in the Klamath Basin, at around $32 million basin-wide, or $185 per acre (Doremus & Tarlock, 2008). A farmer who was willing to store the same quantity of acre-feet - 2.1, on average - (Marshall & Flug 2005) needed to irrigate a typical cash crop like grain or alfalfa, would be able to generate nearly half of this average net revenue when the water was in demand, without risking major losses if a crop went bad during the year.

There would clearly be challenges, even from a purely administrative standpoint. As it stands, the WRP enrolls acreage based on its acceptance of landowner bids (USDA, 2013), the submission of which can be a time consuming, confusing process. Obtaining a WRP contract is by no means guaranteed, as bids must be evaluated by a set of criteria, one of which is the overall cost to the government of the bid (USDA, 2013). Less expensive bids may well be prioritized, which will provide an incentive for the USDA to enroll lower quality lands that are cheaper but may not function as effective wetland storage mechanisms.

But as pointed out above, rational economic calculations are only one factor to consider in pushing for a policy to enhance wetland restoration and water storage. The cultural values held by farmers in the basin are equally as important, and perhaps even more so.

Social construction is a theoretical framework in policy theory that seeks to understand how people's preferences are tied to non-monetary, perhaps innate values and traits. These are not captured by economic theory and have been all too often overlooked in the design and establishment of effective public policy (Stone, 1989). Contrary to highly rationalist models of human behavior and decision making, there are emotional, perhaps instinctive factors that play a role in decisions, major and minor. Social construction posits that these factors are rooted in how people in groups construct, or actively perceive, important aspects of their lives that play a role in their overall value structure (Stone, 1989). In short, while they may look at costs and benefits, they also look at their own identity in society, their heritage, and their place in the community.

A simple economic framework would argue that irrigators should see the price for water increase dramatically in drought years, coupled with a decrease in their overall profit margins. This should drive farming firms out of the basin, until a new equilibrium is established (Nicholson 1998). In cases where downstream users need water, there should be a market system that transfers water and money between the upstream irrigators and downstream fishers, as well as between consumptive users and conservation users.

But this does not exist, at least not in any shape resembling the economic ideal. Instead, the ‘water war’ of 2001-2002 crisis was waged, and still threatens to erupt anew even after a decade of more collaborative approaches (Doremus & Tarlock, 2008). Irrigators tend to defend the status quo of maximum diversions, even though a third of them will typically lose money even in a normal water year (Doremus & Tarlock, 2008). Fishers downstream, both tribal and commercial, argue that theirs are the dominant rights, and do not pay significant quantities to irrigators for the idling of their lands. Simply put, water and money are not very fungible, and so not exchanged in the Klamath Basin according to pure economic predictions.

This disconnect is largely tied to values best described in the terms of social construction. As the ‘tamers’ of the west (Doremus & Tarlock, 2008), ranchers and farmers claim an historic right to the inputs they need to maintain their way of life, a way of life that helped (in their view) make the west what it is today. They thus occupy a certain moral high ground, which gives them the ability in society to undermine the claims of others groups in the Klamath Basin with respect to the area’s water resources.

Ultimately, the perspective of the “working landscape” may be critical in uniting the economic, social and environmental concerns that underpin the use of wetlands as a water storage medium. Polasky et al. (2005) argue for the superiority of mixed use landscapes, where conservation objectives are pursued in conjunction with economic utilization. Their conception is that many of the most important conservation goals can hinge on simple, thoughtful alterations to existing land use patterns that place a small, relatively easily mitigated burden on landowners. These can include things like selective logging in lieu of clear-cuts, or leaving crop wastage in place for a period of time prior to plowing it back into the soil. These types of changes can have outsized benefits to the local ecosystem relative to the economic hit taken by landowners (Polasky et al., 2005). In a region such as the Klamath Basin, where politics and culture intersect to produce a volatile conservation framework, such an idea could help alleviate landowner concerns on both the economic and cultural fronts.

Naturally there is likely to be resistance to changing long-standing practices, and Klamath Basin farmers have been known to express strong ties to traditional modes of operation (Doremus & Tarlock, 2008). But in the context of a major change such as dedicating land to water storage, voluntary participants might be expected to be more open to external advice and support. To add to the power the working landscape idea can have for conceptualizing the overall push towards changing land use in UKB, it is important to recognize the growing trend of amenity migration in rural, predominantly agricultural areas. New migrants to the area - particularly retirees or white collar types who may not desire to engage in physically intensive work - may be more willing to produce a ‘crop’ like water that requires few inputs of labor and capital. The purchase of lands by new migrants has already begun to change the broader land use patterns in areas where amenity migrants have become common, as they are often very open to the idea of using their lands to achieve both economic and conservation goals (Abrams and Bliss, 2013). As they have chosen their new home in large part due to its inherent aesthetics and recreational opportunities, they tend to be more willing to take a more active role in using their land to preserve and enhance these qualities.

5.4 Why Wetlands, Not Reservoirs?

The trend in Western North America under conditions imposed by a changing climate is for precipitation deposition to become warmer, more strongly seasonal and more intense - meaning that while more water may come to the Klamath Basin as rain, this will help to shift peak availability of water further into the spring and winter, and exacerbate summer shortages, when the precipitation received may dwindle unpredictably and perhaps dramatically.

Additionally, a growing general legislative willingness to reserve natural resources, particularly water, for conservation use, has helped increase baseline demands far beyond those of agriculture. The provisions of the Endangered Species Act are unlikely to be repealed or weakened in the short run, which for the Klamath Basin means that minimum in-stream flows are almost certain to remain sufficiently high that junior water rights holders will see reductions and shutoffs of their water flows more and more frequently and ever sooner in the year, if trends continue.

But although overall supply will become more seasonally volatile and demand will remain the same or increase, the total volume of water that passes down the Klamath

River below Iron Gate Dam and on into the Pacific will, in most years, be theoretically sufficient to meet the majority of the demands placed upon it. Given this, the pressing issue becomes how to keep this water in the watershed for a longer period of time, so that the volume available for diversion out of the system stays high enough to meet demand for a greater portion of the year than is currently typical. Boosting available storage is the only conceivable human-controllable solution to this problem, given current technology.

Wetlands are an excellent water storage mechanism choice for the Upper Klamath Basin for several reasons. First and foremost, the data collected here indicates that there is a large area in the basin that naturally functions as wetlands, which can reduce the costs associated with engineering a storage solution from scratch, as in, say, a reservoir. This means that actively increasing storage can be achieved fairly rapidly, especially in areas where existing infrastructure such as a levee network already exists. Second, a major source of water loss in seasonal wetlands is due to soil absorption, but this loss is not the same as a loss due to evaporation, because water that percolates into and through substrate soil largely remains in the watershed system, either by slowly making its way down an elevation gradient to another body of water - say the Klamath River or one of its tributaries - or by recharging groundwater supplies in the aquifer underlying the basin. The first pathway eventually results in slightly higher in-stream flows or the water likely making it into another storage system. The second allows for groundwater extraction through a system of wells and pumps, which can help bolster surface waters or be directly applied to irrigation projects.

Third, wetlands serve a wide variety of natural functions that lend themselves to the provision of ecosystem services, many of which are of economic importance in the Klamath Basin. Amenity migration facilitated by the retirement boom, low cost of land and housing in rural areas, and telecommunications technology is increasingly bringing affluent individuals and families to rural lands (Gosnell & Abrams, 2009). Habitat provision in wetlands attracts vast quantities of waterfowl to the Klamath Basin in most years, which is a source of income for anyone involved in supporting the outdoor industries, particularly hunting and birdwatching (Doremus & Tarlock, 2008). And increased filtration of nutrients helps protect downstream waters from contamination by agricultural waste products (Aldous et al., 2007, Duff et al., 2009), an issue that is garnering increasing attention from federal regulators and can conceivably result in future costs being imposed upon local agriculturists, as is now the experience in the Chesapeake Bay watershed, where high nutrient concentrations have dramatically degraded the local environment (Chesapeake Bay Program, 2013).

There are, naturally, several strands of objection that can be raised to this proposed policy and management regime. Aside from obvious concerns about the accuracy of the data analysis that estimates the potential benefits, which were treated in the sources of error section, and the similarly obvious moral or philosophical arguments that seek demand side solutions to the problem of water allocations in the Klamath Basin, there are practical problems that face this particular attempt at framing a supply-side solution.

A significant source of loss in terms of stored water inevitably comes from evaporation. Especially in summer, when the sun is present in the sky for longer periods of time and the Earth's axial tilt presents a more direct angle between the sun and the top of the planet's atmosphere, promoting enhanced penetration of electromagnetic energy, more water is subjected to temperature increases that promote evaporation (Wallace & Hobbs, 2006). In addition, plants are highly photosynthetic in the summer, and take up large amounts of water both to support growth and to provide cooling during the warmest parts of the day. These factors mean that the inclusive June - September timeframe may well see 50% of the original wetland water volume disappear into the atmosphere, with shallower waters evaporating more quickly due to the lack of insulation provided by upper layers to lower (Mayer, 2005).

The nature of an engineered reservoir is such that its capacity and throughput can be explicitly managed to achieve management objectives. Given sufficient flows to fill the reservoir, the water levels can then be controlled with a high degree of precision. In some ways, Klamath Lake provides an excellent example of this dynamic. Headgates retain water in the lake to some fraction of its maximum storage capacity, and release it as needed to meet the demands of irrigation and in-stream flows (Doremus & Tarlock, 2008). If the latter (coming from tributary rivers below the lake) are insufficient to meet the needs of fish in the Klamath River, then water can be released at the expense of lake levels. Similarly, irrigation water is diverted into the Klamath Reclamation Project when flows are not needed downstream and lake levels are sufficiently high to protect the endangered Suckers in the confines of the lake.

Reservoirs have long been the traditional, go-to solution for water storage that utilizes the natural terrain. There are also side benefits associated with reservoir storage that go beyond predictability and efficiency. Reservoirs with a sufficiently high dam can effectively host a hydroelectric power plant, providing plentiful and cheap energy for many decades. This has previously been the case in the Klamath Basin, where a series of reservoirs below Klamath Lake held hydroelectric infrastructure that provided extremely low cost power to irrigators in order to power water delivery systems (Doremus & Tarlock, 2008). Reservoirs of sufficient depth and surface area are also magnets for amenity dollars, as they can be stocked with fish and enhanced with beaches to provide significant recreation potential above and beyond that offered by swimming and motorized activities.

But while reservoirs may, based on the above, seem like an ideal storage solution, there are some serious issues that arise in reservoir construction and operation that make them less attractive than wetlands, in some ways that are relatively unique to the Klamath Basin. Ultimately, these downsides are arguably far more detrimental than those of wetland restoration, and so boost the latter solution's stock when it comes to efficient, beneficial water storage.

First, there is the issue of the ecological damage wrought by dams and constructed reservoirs. It is generally recognized in most industrialized nations that traditional dam-and-reservoir systems have numerous detrimental side effects on local hydrological conditions. For one, there is the thermal stratification in the reservoir that damages the ability for aquatic life to persist in much of the reservoir and also tends to alter temperatures downstream for some distance (Flug & Campbell, 2005).

One of the worst side effects of a reservoir is that it usually badly restricts the movement of species throughout its footprint and the watershed as a whole. Salmon and other anadromous fish used to range far into the Klamath Basin, beyond Klamath Lake and into its tributaries (Tate et al., 2005, Sullivan et al., 2009). This ended once the main stem was dammed in Northern California, and they are now extirpated in much of their former habitat. Other dams, coupled with the draining of the former Lower Klamath Lake, helped reduce vital habitat for the native Sucker fish so much that they were pushed to the brink of extinction, resulting in their listing under the Endangered Species Act (Cooperman & Markle, 2004).

Even more than the ecological damage caused by dam-and-reservoir systems, there is another factor that makes the construction of dams particularly difficult in the Upper Klamath Basin: terrain. Klamath is an inversion of the typical watershed, which is steep towards its headwaters and more gradual towards its outlet into the sea (Doremus & Tarlock, 2008). Its main canyons and other areas desirable for dam projects are located far downstream in the Lower Klamath, which is sufficiently rugged and undeveloped to post major problems for any effort to build dams, as well as being too far away from the agriculturally viable portions of the basin to be of much use.

Klamath Lake is the first major body of water in the course of the Klamath River's tributaries, and is characteristic of many of the area's lakes: shallow. The waters of the area are so shallow that the Upper Basin used to be largely covered by a massive lake, which was decimated by only a fairly small drop in water levels thousands of years in the past (Doremus & Tarlock, 2008). Installing a reservoir along one of the tributaries of the Klamath would involve quite significant construction efforts, which would cost a great deal of money, and still be fairly inefficient when compared to a typical dam system which sees a valley inundated to a great depth with the pouring of concrete at one end.

Wetlands, by contrast, are ideal storage mechanisms in the Upper Klamath Basin due to their natural prevalence in the area. The satellite imagery demonstrates that much of the basin's lands simply flood naturally, retaining water all on their own. The past history of the basin also indicates that wetlands are a typical feature of the landscape, earning the Upper Basin the moniker of being a 'Western Everglades' (Doremus & Tarlock, 2008). To actively store water in wetlands, particularly in areas where levee infrastructure already exists, may well simply involve a management decision and the suspension of cropping activities on that land in favor of growing water. Where levees do not exist, fairly simple construction projects - perhaps even subsidized by the federal government as part of its stated policy to restore wetlands - could erect the structures needed to hold water at a depth of several feet.

Restoring/constructing such wetlands would not be a perfect solution to the water storage problem, nor would it magically fix all the problems in the basin. The data indicates that a significant fraction of the water needs for Klamath Reclamation Project irrigation can be stored in readily available wetlands at the start of summer, with half of that remaining by the end to be carried over to the next year, if needed. This does not solve the water shortage problem in the area. But it has the potential to mitigate shortages in a below average or even drought year, at a relatively low cost. In addition, positive spillover effects add yet another layer of desirability to wetlands (Mitsch & Gosselink, 2000).

5.5 Need for Further Research

Further research would be needed in order to more effectively assess whether the Upper Klamath Basin should put a policy of water storage via wetland restoration on private and public lands into practice. The ultimate downfall of Landsat data is its relatively coarse spatial resolution. A 30 meter by 30 meter area, represented as a single pixel on a computer screen, effectively compresses 900 square meters, or almost a full acre-foot of water if the pixel represented an entire area flooded to a depth of a bit more than one meter, into a tiny dot difficult to visually pick up. It requires a large collection of such dots to trigger a response in the human eye that interprets an area as having a relatively large concentration of what is being represented by these pixels, in this case, shallow water.

Unfortunately there are limitations to the processing power, data storage, and analyst time available to work on such imagery, and an area the size of the Upper Klamath Basin already involves millions of such pixels. Obtaining higher resolution data for the entire study area is possible, and yet would exponentially increase the inputs required to analyze it. Using Landsat data is effectively a compromise between theoretical and practical capabilities, suitable for a large scale reconaissance such as presented here.

However, to optimally select areas to function as restored wetlands and water storage systems, higher resolution imagery is necessary. What a basin-scale remote sensing approach does is to narrow down a broad dataset into several candidate focus areas for further research. Given time and funding the same basic methodology as applied above could be used with data collected from a more modern sensor, such as IKONOS or GeoEye, which are capable of sub-1m meter spatial resolutions and can be targeted as needed. Imagery obtained from these sources could cover the areas identified on Landsat images as being home to high concentrations of wetlands, and identify specific tracts within these focus areas that are the most suitable candidates for restoration and storage operations.

Such a project would allow for ranking candidate conservation sites accurately, by examining the frequency of their exhibiting seasonal wetland behavior (seasonal flooding) during a multi-year period of study. Other variables such as evapotranspiration effects could be more accurately quantified as well (Tang et al., 2009). This would provide excellent baseline data that could be taken into a Geographic Information System and mapped as a variable alongside other criteria, including the biophysical and economic. Such an effort would further enhance the robustness of the dataset and inform optimal management decisions.

Additionally, utilizing these platforms with this high of spatial resolution would allow for accurate tracking of the crop type observed to be planted in candidate areas, if any, and how frequently they were present. Existing libraries of spectral data pertaining to specific plant species and soil types in particular electromagnetic wavelengths are available to ensure the quality of such estimates. This would allow for a further economic assessment of the impacts of this policy to be made, that would more accurately understand the value of a tract of land given typical value of the crop in question.

Conducted effectively, this proposed extension of the research could better assess the extent and location of seasonal wetlands in areas where they are known to exist in concentration. It would also shine a more clear light on the impacts that could be expected from instituting the policy option elucidated above. While this research provides a good jump-off point for such a further research, the technological capabilities of remote sensing and geographic information systems provide an opportunity for far more extensive, nuanced, and precise research than has been conducted here, with greater benefits in producing an optimal policy initiative.

Another profitable avenue of future research would examine the impact climate change could be expected to haveo n the UKB system. While future climate conditions are inherently uncertain and difficult to predict, a safe bet appears to be that even where annual precipitation increases it will tend to be warmer and more seasonal. This means that the Klamath may become increasingly reliant not on snowpack, which can hold water above the basin into later months of April and May, but on rainfall occurring in the winter months of December, January, and February. This would create a significant incentive for water managers in UKB to emphasize storage, as the storage function in snowpack lost to a warming climate would ultimately mean reduced summer instream flows of such a magnitude that neither irrigation nor fishing interests could meet their minimum requirements even if given the full allocation of that season's water. Increasing storage in wetlands could serve as a viable means of mitigating this impact of climate change, though to what degree they could take on this role and to what extent they might need to must be left to future research to understand.

Additionally, research into the optimal instream flow requirements for supporting salmonid lifecycles in the Klamath Watershed is sorely needed. The most recent Biological Opinion, released in summer 2013, led to a complete cut-off of the National Wildlife Refuges from water deliveries in spring (Mayer and Mauser, Personal Communication, 2013). This is because water managers are being required to use the more stringent NMFS minimum flow recommendations, which have allocated virtually every drop of water available through the Klamath Project. In fact, the idea of using more than ten thousand acres to store upwards of 60,000 acre-feet of water has been examined by professionals with experience in UKB, but the idea is “dead on arrival” because of the 2013 Bi-Op (Mayer and Mauser, Personal Communication, 2013). While this ban on refuge deliveries would not directly apply to private landowners who through a combination of public and private conservation easements and/or other incentives agreed to use their lands for storage, it would seriously hinder the possible policy examined in this work as the bulk of lands available for storage are located in the federal refuges. A better scientific and public understanding of the needs of salmon downstream is needed, or else any proposal to store water in wetlands is likely to be a non-starter, as only the wettest years would allow for spring water deliveries to locations optimized for storage.

Another key avenue of future research will be to examine how voluntary participation in a wetland water storage program could be increased by paying attention to the social and cultural particularities of the region and in the relationship between farmers, their land and profession, and broader society. This research needs to examine how it might be possible to shift social construction of farming in the region such that landowners would find it mentally and socially appealing to store water in lieu of growing a crop.

A farmer whose heritage and personal choices in life have both been tied to farming, to cultivating and sustaining life, may well find it anathema to consider abandoning this way of life to do virtually anything else. For such a farmer, existence as a member of their community could be possible only if they continue the activity that defines them, that provides their identity and their peer group, to say nothing of their family history. It has been pointed out that farming is often more a calling than a profession, as to endure the unending stresses, anxieties, and failures inherent in relying upon a fickle mother nature is something no one without incredible reserves of inner strength can endure, if they have any choice in the matter.

For such people, asking them to simply idle their lands, even if doing so provides an income stream, may not be enough. They need the water to grow their crops, and they need to grow their crops to fulfill their place in the world. Where economic theory can only point out the rational course of action, and expect them to follow it, social construction framework may shine a light on a means of providing them with a meaningful replacement activity that can at least partially fall under the same rubric as farming.

It may well then be an essential component of a wetland restoration for water storage policy initiative to help establish a positively viewed relationship between storing water and farming, in a sense promoting the idea of a crop farmer shifting to being a water farmer - a calling no less vital to the welfare of the agricultural community than that of a crop farmer.

This, quite obviously, is a concept that will seem a bit more than hokey to some. After all, one does not traditionally 'farm' water - it comes from the sky, and is guaranteed as a fundamental right to those whose ancestors claimed it. But, in a sense, all farmers are effectively 'farming' sunlight, water, and nutrients, combining them in the form of plant matter and through the medium of soil into a sort of compact natural battery: plants. Energy and matter are simply being rearranged through their efforts into a form which living things like we humans can digest, and so producing plants is itself a component activity that is one important chain in a complex sequence that allows life as we know it to persist and thrive.

Water, in this sense, is merely single - albeit vital - element in the farming equation, a sub-component necessary to produce a higher level, but still subordinate, component of all life. A crop farmer who shifts to farming water can effectively be seen as simply shifting crops, with the product of their labor moving on to support other producers in their activities which ultimately result in concentrated organic energy bound up in the living things that go on our plates, and thus power our ability to do all we do in daily life. Under this conception, just as an alfalfa farmer produces feed for various livestock herds, which through their meat and milk and strength and fur provide vital products for human consumption, so would a water farmer provide a vital feedstock for the alfalfa farmer.

Describing the shift in social construction that would need to take place in order to make this conception viable is easier said than done, however, and requires significant investment in terms of research effort to identify whether such a shift is possible and how it might take place. Only further research can provide information needed to make such a determination.

Chapter 6 Conclusion

Ultimately, any decision on how to develop the future of the Klamath Basin is entirely up to the resident stakeholders. Only they can decide what they value, how much, and whether they wish to pursue conflict in the hopes of achieving final victory.

The annual supply of water in UKB has been rendered too dependent on monthly precipitation and the yearly bounty of water from snowpack melting for comfort, with the result that even a very wet spring may not alleviate late-summer shortfalls if conditions are too dry during these months. This situation has been partly caused, and certainly exacerbated by, the loss of the basin's historic wetlands. These tended to buffer the flow of water through the watershed, keeping water higher in the basin later into the summer. Local species, some of which are now endangered, adapted to these conditions. Early migrants, whose agricultural needs could be well served by skilful use of appropriate cropping systems tied to local conditions and social needs, began to tax the system - but not to the point seen in the post World War II period, when the Klamath Reclamation

Project actively drained natural wetlands and converted them to agricultural use (Doremus & Tarlock, 2008). This caused the supply of storage to dwindle, and naturally affected stream flow dynamics. Reversing this loss is desirable for many reasons, but storage is perhaps the most compelling, at least in local terms.

This thesis has endeavored to present a possible mitigation option that is supported by a basin-scale scientific assessment of the existing inventory of lands with a strong tendency to flood during the wet season. The fundamental assumption, which appears backed by the current scientific understanding of wetlands both in and out of the Klamath Basin, is that such lands function as temporary wetlands which are naturally efficient at retaining water. Given this assumption, it appears that there is a significant possibility of managing these lands as wetlands to store water from year to year in hopes of partial amelioration of future droughts.

The analysis of the satellite imagery relies upon the principles of remote sensing and digital image processing to obtain reliable data, and a semi-automated classification process to delineate the extent of lands that can be classified as wetlands in both the spring and summer seasons from 2000-2012. A comparison of lands that are wet in spring but dry in summer indicates the lands that are most likely to be viable restored wetlands that can be utilized for storage purposes. The number of pixels that demonstrate this defining characteristic indicates that 60,000 acres of land are on average present basin-wide that meet these requirements.

Distinct patterns in the grouping of these identified lands show that there are natural concentrations of wetlands in the areas surrounding Tule Lake, Lower Klamath, Upper Klamath, and Klamath Marsh refuges. While any specific individual acre's propensity to be a wetland was not examined due to lack of sufficient resolution in the satellite imagery, the overall quantity of wetland acres in these regions was estimable which points the way to more focused satellite or in-person reconaissance in the future to identify the specific lands that are viable storage sites. All in all, taking a lower bound estimate of the acreage located in these specific areas, it was found that approximately 30,000 acres of probable wetlands are typically found in and around these refuges, on public and private lands.

Sufficient volumes of water pass through the Klamath Basin in most years to meet all demands, from irrigation to municipal to in-stream flows for fish. But as it stands, there is insufficient storage to retain significant quantities of water from year to year. This lack of storage and the inability of the region's water supply to meet demand in drought years combines, as in 2001-2002, to cause significant competition, even conflict, over the available water resources.

With under 500,000 acre-feet of water storage generally available, total demands (including in-stream flows) reaching 1 million acre-feet each year, and total water passing through the basin in an average year coming to 1.18 million acre-feet, but under 800,000 acre-feet in a drought like that of 2001, there is a clear need to store surplus water.

30,000 acres of wetlands can, assuming two feet of water is the average level at the start of summer, totaling 60,000 acre-feet pulled from winter and spring precipitation and snowmelt in an average year, retain 30,000 acre-feet through the dry season and on into the succeeding autumn, when the level will begin to replenish again due to new precipitation. Less than the 60,000 acre-feet needed in the first year will be needed in the second and following, due to the existing saturation of substrate soils, so long as these are never completely dried. Thus, inter-year storage, given past patterns of water flow in the Upper Klamath Basin, ensure 30,000 acre-feet of availability from year to year, increasing baseline storage levels by nearly 6%.

This is insufficient to completely mitigate a serious drought on the level of 1992 or 1996, but is sufficient to significantly mitigate a drought on the scale of that seen in 2001. This storage, due to the nature of water in the basin being used either for in-stream flows or for consumptive uses, could produce an in-stream flow boost necessary to meet FERC minimums throughout the month of August while simultaneously obviating the need for the water to achieve this boost, which may be required to safeguard fish, from being taken away from agricultural diversions. Given typical average application rates of 2.1 acre-feet per acre and average gross revenues of $560 per acre, this indicates that more than $8 million in agricultural revenues, approximately 7-8% of the basin total, could be protected by this storage.

Effecting this storage would require a policy initiative targeting both public and private lands in and around these refuges. Public lands in the basin wildlife refuges can be managed as wetlands with a storage function so long as this does not impede their use as waterfowl habitat supporting the Pacific Flyway migrations. However, large tracts of public lands on these refuges are traditionally leased to farmers who use their rich soils to grow cash crops. The detritus of these crops becomes forage feed for migratory waterfowl. Any acreage managed as permanent wetlands will be unavailable for such leasing arrangements. This may lead to resistance on the part of farmers who typically used these lands for this purpose, and a reduction in forage feed might detrimentally impact waterfowl.

However, these ecological and economic downsides would be ameliorated to an extent - difficult to estimate in monetary terms - by ecosystem services provided by these wetlands. These include their draw to ecotourists and amenity migrants, nutrient filtration which can mitigate toxic algal blooms downstream, and habitat for local and migratory creatures.

On private lands, voluntary participation in the water storage program would hinge on two factors, one economic and the other social. Voluntary enrollment, supported by a local agency or non-profit, in the USDA Wetlands Reserve Program, would provide cash benefits equal to the bare-land rental value of the lands enrolled. Participation in a regional water bank would allow landowners to gain an active economic benefit from selling water voluntarily stored for later release. But perhaps more importantly, an effort would have to be made to reframe the issue of storing water in terms closer to the ideal of 'growing water,' in order to help provide a social incentive for farmers whose social and community identity is wrapped up in their role as farmers. A reconstruction of the concept of farming to equate water farming with other forms of farming would be needed to help break down barriers towards participation.

The life of a farmer is not easy. Nature is often unpredictable in ways that directly and adversely affect farming operations. A bad year can see an entire crop destroyed, and the farmer either take a loss or break even due to the use of crop insurance. A good year often means simply having excess funds to sock away as a reserve against an inevitable bad year. This inherent uncertainty provides a strong incentive to mitigate the financial risk wherever possible. Insurance helps, but can be costly if used too often. Renting land to other farmers is an option, yet on a year to year basis is still tied to the risky farming enterprise.

In effect, then, so long as an individual farmer's risk perception is sufficiently high that enrollment in a conservation easement and participation in a water bank are at least equivalent in terms of pure financial considerations, it is reasonable to believe that participation would be common if a policy initiative popularized and simplified these systems. Successfully convincing farmers of the potential material benefits of such a policy would go some distance towards reducing opposition to it, and help contribute to the goal of accumulating additional storage alongside wetland restoration in the Klamath Basin.

To ensure that lands that are desirable locations for water storage enter into the WRP, it would likely be necessary to have a local government, university, or non-profit group specialize in supporting WRP bids. This group could conceivably perform outreach with farmers, help construct bids, and perhaps even work directly with the responsible agency within the USDA to help smooth the bid process so that the overall objectives of the policy – wetland restoration coupled with water storage – could be achieved. Coupled with the existing water bank system, which could be restructured to accommodate increased storage or replaced by a newer, more up-to-date system, WRP enrollment could help boost participation rates. Private lands may prove to be the key in the success of this policy.

Another possibility in terms of providing an income-based, economic incentive to participate in conservation easements could involve the emerging phenomena of payments for ecosystem services paid to landowners by corporations who have an interest in ‘greening’ their image. As some of the most classically rational economic actors in existence, companies have a clear interest in maintaining a certain image, if only as a means of protecting the reputation of their brand. With the growth of the environmental movement’s power, being perceived as a ‘green’ business has a certain value. No less powerful a company than Google, for example, has dedicated a large proportion of its revenues in solar energy investments (Upson 2007). The fast food chain McDonald’s partnered with Greenpeace to pressure a major supplier in its supply chain to adopt environmental policies that were less damaging to the Amazon rainforest (Tercek, 2013). Such investments of time and money are not easily explained except as attempts by major brands to preserve their reputation in the face of possible consumer backlash against brands perceived as contributing to environmental degradation.

Granted, such moves on the part of Google and McDonalds may very well be driven by less-than-ideal motivations. It is more likely than not that such institutions whose primary objective is the pursuit of profit make the decision to ‘green’ their image not out of a true commitment to being moral, ethical citizens of the world, but out of a strictly amoral calculation of their interests (Crane, 2000). However, from the perspectives of the landowner who similarly needs to generate revenue in order to survive and the water manager who needs additional storage in the UKB, the move towards 'greening' - whether or not it is driven by moral considerations - presents an opportunity to bring income to the area. Partnering with corporate interests who might themselves be willing to fund a conservation easement that restores wetlands in the area could be a viable strategy, particularly if popular demands for companies to go green continue to gain traction in the marketplace. An effort to put this policy of wetland restoration for water storage into practice could seek corporate sponsors who would gain the ability to advertise their support for the restoration of some number of wetlands in the Upper Klamath Basin, with all the ecosystem services restoration that would entail. This might have also present additional side benefits in terms of allowing landowners a more flexible pathway to restoration for storage than might be allowed by federal regulators enforcing the terms of a conservation easement contract. Politically and philosophically, a basin landowner might look more favorably and with more trust at a corporate contract than one emerging from state or federal agencies.

Ultimately, such a wetlands restoration and water storage program appears both feasible and potentially beneficial economically to the Upper Klamath Basin. It may help reduce conflicts over water in the region, preserving both environmental and social values. It would achieve national goals of wetland restoration, and promote stability in a troubled area.

Bibliography

Abrams, Jesse, & Bliss, John C. (2013). Amenity Landownership, Land Use Change, and the Re-Creation of "Working Landscapes." Society and Natural Resources: An International Journal 26:7, 845-859

Aldous, Allison R., Craft, Christopher B., Stevens, Carla J., Barry, Matthew J., Bach, Leslie B. (2007). Soil phosphorous release from a restoration wetland in Upper Klamath Lake, Oregon. Wetlands 27 (4), 1025-1035.

Aldous, Allison, McCormick, Paul, Ferguson, Chad, Graham, Sean, Craft, Chris. (2005). Hydrologic Regime Controls Soil Phosphorus Fluxed in Restoration and Undisturbed Wetlands. Restoration Ecology 13 (2), 341-347.

Ando, Amy, Camm, Jeffrey, Polasky, Stephen, Solow, Andrew. (1998). Species Distributions, Land Values, and Efficient Conservation. *Science*, New Series 279 5359, 2126-2128.

Ardón, Marcelo, Montanari, Shaena, Morse, Jennifer L., Doyle, Martin W., Bernhardt, Emily S. (2010). Phosphorous export from a restored wetland ecosystem in response to natural and experimental hydrologic fluctuations. Journal of Geophysical Research 115.

Ardón, Marcelo, Morse, Jennifer L., Doyle, Martin W., Bernhardt, Emily S. (2010). The Water Quality Consequences of Restoring Wetland Hydrology to a Large Agricultural Watershed in the Southeastern Coastal Plain. Ecosystems 13, 1060-1078.

Babbar-Sebens, Meghna, Barr, Robert C., Tedesco, Lenore P., Anderson Milo. (2013). Spatial identification and optimization of upland wetlands in agricultural watersheds. Ecological Engineering 52, 130-142.

Baker, Corey, Lawrence, Rick, Montagne, Clifford, Patten, Duncan. (2006). Mapping wetlands and riparian areas using Landsat imagery and decision-tree based models. Wetlands 26 (2), 465-474.

Bradbury, J. Platt, Colman, Steven M., Reynolds, Richard L. (2004). The history of recent limnological changes and human impact on Upper Klamath Lake, Oregon. Journal of Paleolimnology 31, 151-165.

Burke, Susan M., Adams, Richard M., Wallender, Wesley W. (2004). Water banks and environmental water demands: Case of the Klamath Project. Water Resources Research 40.

Campbell, Sharon G., Flug, Marshall, Hanna, R. Blair. Evaluating Water Allocations for Drought Management. United States Geological Survey, Biological Resources Division, Midcontinent Ecological Science Center.

Campbell, Sharon G., Hanna, R. Blair, Flug, Marshall, Scott, John. F. (2001). Modeling Klamath River System Operations for Quantity and Quality. Journal of Water Resources Planning & Management 127, 284-294.

Castro, A.J., Martín-López, B., Garcia-LLorente, M., Aguilera, P.A., López, E., Cabello, J. (2011). Social preferences regarding the delivery of ecosystem services in a semiarid Mediterranean region. Journal of Arid Environments 75, 1201-1208.

Ciotti, D., Griffith, S.M., Kann, J., Baham, J. (2010). Nutrient Sediment Transport on Flood-Irrigated Pasture in the Klamath Basin, Oregon. Rangeland Ecology & Management 63 (3) 308-316.

Cooperman, Michael S. & Markle, Douglas F. (2004). Abundance, size, and feeding success of larval shortnose suckers and Lost River suckers from different habitats of the littoral zone of Upper Klamath Lake. Environmental Biology of Fishes 71, 365-377.

Costanza, Robert, d'Arge, Ralph, de Groot, Rudolf, Farber, Stephen, Grasso, Monica, Handen, Bruce, Limburg, Karin, Naeem, Shahit, O'Neill, Robert V., Paruelo, Jose, Raskin, Robert G., Sutten, Paul, van den Belt, Marjan. (1997). The value of the world's ecosystem services and natural capital. *Nature* 385 (15).

Crandall, John D., Bach, Leslie B., Rudd, Nathan, Stern, Mark, Barry, Matt. (2008). Response of Larval Lost River and Shortnose Suckers to Wetland Restoration at the Williamson River Delta, Oregon. Transactions of the American Fisheries Society 137 (2), 402-416.

Crane, Andrew. (2000). Corporate Greening as Amoralization. Organization Studies 21:4, 673-696

Crépin, Anne-Sophie. (2005). Incentives for wetland creation. Journal of Environmental Economics and Management 50, 598-616.

Diebel, Matthew W., Maxted, Jeffrey T., Nowak, Peter J., Vander Zanden, M. Jake. (2008). Landscape Planning for Agricultural Nonpoint Source Pollution Reduction I: A Geographical Allocation Framework. Environmental Management 42, 789-802.

Doremus, Holly D. & Tarlock, A. Dan. (2008). Water War in the Klamath Basin: Macho Law, Combat Biology, and Dirty Politics. Island Press

Duff, John H., Carpenter, Kurt D., Snyder, Daniel T., Lee, Karl K., Avanzino, Ronald J., Triska, Frank J. (2009). Phosphorous and Nitrogen Legacy in a Restoration Wetland, Upper Klamath Lake, Oregon. Wetlands 29 (2), 735-746.

Dunne, E.J., Clark, M.W., Mitchell, J., Jawitz, J.W., Reddy, K.R. (2010). Soil phosphorous flux from emergent marsh wetlands and surrounding grazed pasture uplands. Ecological Engineering 36, 1392-1400.

Eilers, J.M., Kann, J., Cornett, J., Moser, K., St. Amand, A. (2004). Paleolimnological evidence of change in a shallow, hypereutrophic lake: Upper Klamath Lake, Oregon, USA. Hydrobiologia 520, 7-18.

Ely, Craig R. & Takekawa, John Y. (1996). Geographic Variation in Migratory Behavior of Greater White-Fronted Geese (Anser albifrons). The Auk 113 (4), 889-901.

Euliss Jr., Ned H., Smith, Loren M., Liu, Shuguang, Duffy, Walter G., Faulkner, Stephen P., Gleason, Robert A., Eckles, S. Diane. (2011). Integrating estimates of ecosystem services from conservation programs and practices into models for decision makers. Ecological Applications, Supplement, 21 (3), S128-S134.

Fernández-Prieto, D., & Finlayson, C.M. (2009). Earth Observation and wetlands. Journal of Environmental Management 90, 2119-2120.

Fleskes, Joseph P., Mauser, David M., Yee, Julie L., Blehert, David S., Yarris, Gregory S. (2010). Flightless and Post-Molt Survival and Movements of Female Mallards Molding in Klamath Basin. Waterbirds 33 (2), 208-220.

Flint, Lorraine E. & Flint, Alan L. (2008). A Basin-Scale Approach to Estimating Stream Temperatures of Tributaries to the Lower Klamath River, California. Journal of Environmental Quality 37 (57).

Flug, Marshall & Campbell, Sharon. (2005). Drought Allocations Using the Systems Impact Assessment Model: Klamath River. Journal of Water Resources Planning and Management 131, 110-115.

Frohn, Robert C., Reif, Molly, Lane, Charles, Autrey, Brad. (2009). Satellite remote sensing of isolated wetlands using object-oriented classification of Landsat-7 data. Wetlands 29 (3), 931-941.

Gosnell, Hannah & Kelley, Erin C. (2010). Peace on the river? Social-ecological restoration and large dam removal in the Klamath Basin, USA. Water Alternatives 3 (2), 362-383.

Gosnell, Hannah & Abrams, Jesse. (2009). Amenity migration: diverse conceptualizations of drivers, socioeconomic dimensions, and emerging challenges. Geojournal.

Gleason, R.A., Euliss Jr., N.H., Tangen, B.A., Laubhan, M.K., Browne, B.A. (2011). USDA conservation program and practice effects on wetland ecosystem services in the Prairie Pothole Region. Ecological Applications, Supplement, 21 (3), S65-S81.

Graham, Sean A., Craft, Christopher B., McCormick, Paul V., Aldous, Allison. (2005). Forms and accumulation of soil P in natural and recently restored peatlands - Upper Klamath Lake, Oregon, USA. Wetlands, 25 (3), 594-606.

Grings, F., Salvia, M., Karszenbaum, H., Ferrazzoli, P., Kandus, P., Perna, P. (2009). Exploring the capacity of radar remote sensing to estimate wetland marshes water storage. Journal of Environmental Management 9, 2189-2198.

Hansson, Lars-Anders, Brönmark, Christer, Nilsson, P. Anders, Åbjörnsson, Kajsa. (2005). Conflicting demands on wetland ecosystem services: nutrient retention, biodiversity, or both? Freshwater Biology 50, 705-714.

Heimlich, Ralph E., Wiebe, Keith D. Claassen, Roger, Gadsby, Dwight, House, Robert M. (1998). Wetlands and Agriculture: Private Interest and Public Benefits. United States Department of Agriculture.

Hoehn, John P., Lupi, Frank, Kaplowitz, Michael D. (2003). Untying a Lancastrian bundle: valuing ecosystems and ecosystem services for wetland mitigation. Journal of Environmental Management 68, 263-272.

Humphries, Hope C., Bourgeron, Patrick S., Reynolds, Keith M. (2010). Sensitivity Analysis of Land Unit Suitability for Conservation Using a Knowledge-Based System. Environmental Management 46, 225-236.

Jakubowski, Andrew R., Casler, Michael D., Jackson, Randall D. (2010). The Benefits of Harvesting Wetland Invaders for Cellulosic Biofuel: An Ecosystem Services Perspective. Restoration Ecology 18 (6), 789-795.

Jensen, John R. (2007). Remote Sensing of the Environment, an Earth Resource Perspective. Prentice Hall, New Jersey.

Jensen, John R. (2004). Introductory Digital Image Processing, 3rd Edition. Prentice Hall

Kahara, Sharon N. & Duffy, Walter G. (2011). Wetland ecosystem services in California's Central Valley and implications for the Wetland Reserve Program. Ecological Applications 21 (3), 518-530.

Krasnostein, A.L. & Oldham, C.E. (2004). Predicting wetland water storage. Water Resources Research 40.

Kulawardhana, R.W., Thenkabail, P.S., Vithanage, J., Biradar, C., Islam, Md A., Gunasinghe, S., Alankara, R. Evaluation of the Wetland Mapping Methods using Landsat ETM+ and SRTM Data. International Water Management Institute.

Mayer, Tim D. (2005). Water-quality impacts of wetland management in the Lower Klamath National Wildlife Refuge, Oregon and California, USA. Wetlands 25 (3), 697-712.

Mayer, Tim D., Thomasson, Ron. (2004). Fall water requirements for seasonal diked wetlands at Lower Klamath National Wildlife Refuge. Wetlands 24 (1), 92-103.

Mitsch, William, Gosselink, James (2000). Wetlands, 4th Edition. John Wiley & Sons, Inc.

Moreno-Mateos, David, Power, Mary E., Comín, Francisco A., Yockteng, Roxana. (2012). Structural and Functional Loss in Restored Wetland Ecosystems. PLoS Biology 10 (1).

Mustafa, Atif & Scholz, Miklos. (2011). Nutrient Accumulation in *Typha latifolia* L. and Sediment of a Representative Integrated Constructed Wetland. Water Air Soil Pollution 219, 329-341.

National Research Council of the National Academies. (2012). Using Science as Evidence in Public Policy. The National Academies Press

Nicholson, Walter. 1998. Microeconomic Theory: Basic Principles and Extensions 7th Edition. Harcourt Brace & Company

North American Space Administration. 2013. Landsat Science Data Users Handbook. Accessed January 2012 http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf

Owen, Dave. (2008). Water War: Explaining the Klamath Controversy. Conservation Biology 22 (6), 1664-1666.

Polasky, Stephen, Nelson, Erik, Lonsdorf, Eric, Fackler, Paul, Starfield, Anthony. (2005). Conserving Species in a Working Landscape: Land Use with Biological and Economic Objectives. Ecological Applications 15:4, 1387-1401

Roberts, Michael J. & Bueholz, Shawn. (2006). Slippage in the Conservation Reserve Program or Spurious Correlation? A Rejoinder. American Journal of Agricultural Economics, 88 2. 512-514.

Shook, Kevin, Pomeroy, John W., Spence, Christopher, Boychuck, Lyle. 2013. Storage dynamics simulations in prairie wetland hydrology models: evaluation and parameterization. Hydrological Processes 27, 1875-1889.

Smith, Loren M., Euliss Jr., Ned H., Wilcox, Douglas A., Brinson, Mark M. (2008). Application of a Geomorphic and Temporal Perspective to Wetland Management in North America. Wetlands 28 (3), 563-577.

Söderqvist, Tore, Mitsch, William J., Turner, R. Kerry. (2000). Valuation of wetlands in a landscape and institutional perspective. Ecological Economics 35, 1-6.

Stone, Deborah. (1998). Policy Paradox: The Art of Political Decision Making, Revised Edition. W.W. Norton and Company

Sullivan, Annett B., Snyder, Dean M., Rounds, Stewart A. (2009). Controls on biochemical oxygen demand in the upper Klamath River, Oregon. Chemical Geology 269 12-21.

Tang, Q., Rosenberg, E.A., Lettenmaier, D.P. (2009). Use of satellite data to assess the impacts of irrigation withdrawals on Upper Klamath Lake, Oregon. Hydrology and Earth System Science 13, 617-627.

Tercek, Mark, & Adams, Jonathan S. (2013). Nature's Fortune: How Business and Society Thrive by Investing in Nature. Basic Books

Tanner, Chris C. & Sukias, James P.S. (2011). Multiyear Nutrient Removal Performance of Three Constructed Wetlands Intercepting Tile Drain Flows from Grazed Pastures. Journal of Environmental Quality 40, 620-633.

Tate, Kenneth W., Lancaster, Donald L., Lile, David F. (2007). Assessment of thermal stratification within stream pools as a mechanism to provide refugia for native trout in hot, arid rangelands. Environmental Monitoring Assessment 124, 289-300.

United States Department of Agriculture. Rural Economic Trends Following CRP's Implementation.

United States Department of Agriculture, Farm Service Agency. www.fsa.usda.gov, accessed 2/17/2013.

United States Department of Agriculture, Natural Resource Conservation Service. www.nrcs.usda.gov, accessed 2/18/2013

Upson, Sandra. (2007). The Greening of Google. IEEE Spectrum October 2007, 25-28

Wallace, John M. & Hobbs, Peter V. (2006) Atmospheric Science: An Introductory Survey 2nd Edition. Academic Press

Wooldridge, Jeffrey M. (2003) Introductory Econometrics: A Modern Approach 2nd Edition. Thompson Learning

Zedler, Joy B., & Kercher, Suzanne. (2005). Wetland Resources: Status, Trends, Ecosystem Services, and Restorability. Annual Review of Environment & Resources 30, 39-74.