AN ABSTRACT OF THE THESIS OF

Sara Alice Wyland for the degree of Master of Science in Water Resources Science
Presented on May 21, 2013.
Title: Development of Baseline Data on Oregon’s High Desert Vernal Pools

Abstract approved:

_________________________________________

Ron J. Reuter

Vernal pools are ephemeral surface water wetlands with unique hydrology, ecology and species composition. Rare and endemic species rely on vernal pool habitat due to specialization traits the species possess because they are adapted to the extreme conditions. Many vernal pool basins have been topographically and hydrologically altered and are utilized heavily for cattle, which can lead to deleterious effects to vernal pool ecosystems. Little research has been performed on Oregon’s high desert vernal pools, impeding proper management and protection. This study was conducted to gather baseline data on the pools over the 2011 and 2012 spring to fall seasons. Water quality analysis was performed to determine if differences exist between natural vernal pools, those that have been altered, and anthropogenic water source alternatives in the region, and to see if water chemistry changes as the pools dry down. Some trends were shown, but the data were highly variable within site classifications. General temporal trends of pools showed increases in temperature, turbidity, conductivity and anions, and decreases in dissolved oxygen and oxidation-reduction potential throughout the seasons. Natural pools displayed opposite temporal trends of turbidity and nitrate than other site types, indicating different chemical functioning. Excavations inside basins where water was only present in the excavation had different water chemistry from excavations where water was
overflowing into the natural basin, and from unaltered natural basins, demonstrating impacts of excavated topography. Although some patterns can be recognized, the data was variable and suggest little can be assumed about the water quality status of Oregon’s high desert vernal pools.

A GIS and remote sensing method was developed to quantify the change in water surface area in the high desert at various time points by performing supervised classifications of SPOT images. The method was found to be capable of easily deriving surface areas from the SPOT images, with little potential for error. Water surface areas were extracted from ten SPOT images taken from 2010 to 2013. Surface areas were compared to local climate data to assess for determining factors. The temporal resolution of the preliminary analysis was not high enough to determine causation, but results suggest annual precipitation and timing persistence are important factors in water surface areas.
Master of Science thesis of Sara Alice Wyland presented on May 21, 2013

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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.

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Sara Alice Wyland, Author
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INTRODUCTION TO OREGON’S HIGH DESERT VERNAL POOLS

Sara A. Wyland
1. INTRODUCTION TO OREGON’S HIGH DESERT VERNAL POOLS

1.1. Abstract

Vernal pools are surface water wetlands that undergo an annual cycle of filling, ponding, drying, and desiccation. The unique hydrological regime leads to ecologically important functions, such as serving as breeding and rearing grounds for many species, and the pools tend to become isolated micro-regions of high biodiversity. Species specially adapted to the extreme hydrologic conditions rely on vernal pools for habitat, and they are home to many endemic and rare species. A large amount of vernal pool basins have been altered, primarily to increase the ponding duration for cattle. Physical alteration to the basins also leads to changes in habitat and species composition, reduced amphibian populations, and a favoring of invasive over native plants. Effects of grazing are controversial. Grazing might positively impact native plants by reducing some invasive plant material, but in the vernal pool basins it has been documented to alter the soil profile, increase eutrophic state of the water column through nutrient input, reduce plant richness, and alter species composition.

Vernal pools are not held to the same regulatory standards as year-round wetlands, as they don’t meet the legal criteria for hydrology, soils and vegetation during the dry times of year. Protection that does exist is usually provided by the Endangered Species Act or state-specific legislation, but is limited and usually inadequate for protection of biodiversity. Very little research has been done on Oregon’s high desert vernal pools, but the extent of alteration is high. Whether or not topographical restoration of altered basins would restore ecological functions is unclear. Vernal pools in the region provide water and habitat for many species, with a high amount being rare species, including migratory and non-migratory birds, bats, macro-invertebrates, amphibians and mammals. The importance of seasonal water availability provided by vernal pools is amplified due to the semi-arid climate. Although the surface water including vernal pools has been extensively mapped, mapping of vernal pools specifically has not been
done broadly. A preliminary GIS analysis was conducted to analyze the feasibility of using NWI data to identify the number, locations and level of alteration of vernal pools in the region. The main limitations of the classification system are that the NWI does not adequately differentiate vernal pools from other water system types in the area, and includes historical vernal pool basins that likely do not hold water anymore. GIS processing of the data was used to improve the ability to map vernal pools. Using this method, about four thousand isolated wetlands exist in the study area, and about half of them were altered. The extent of understanding of Oregon’s high desert vernal pools is low, and additional research is needed to assure ecosystems and resources they provide are accounted for and protected.


1.2. Introduction

Vernal pools vary greatly in their distribution, geologic substrate, water quality, hydrology and hydrologic connectivity (seasonally and spatially), management and utilization by flora and fauna. Because form and functions vary by geophysical province, management of vernal pools must be based on ecosystem research in the specific province. Oregon’s high desert vernal pools on public lands are primarily managed by the Bureau of Land Management (BLM) for cattle grazing, as are pools on private lands. There is a lack of research on the ecological functions provided by vernal pools in the region, and possible impacts alterations such as excavations and grazing have on them (Dlugolecki, 2010). This chapter summarizes general information about vernal pools, analyzes the available data on Oregon’s high desert vernal pools east of the Cascade Range, and summarizes a preliminary Geographic Information
System (GIS) analysis performed on National Wetlands Inventory (NWI) data to determine the number of vernal pools in an area, and the extent of anthropogenic alteration done to them.

1.3. Overview of Vernal Pools

Vernal pools are stagnant lentic surface water depressional wetlands which fill in winter months, dry out by the late summer in most years, and often dry out and refill several times in one year (Cook and Hauer, 2007; Clausnitzer and Huddleston, 2002; Tiner, 2003; Zedler, 2003). Vernal pools are globally distributed, and are found in a wide variety of ecosystems, from forests to deserts, but are more common in mid-latitude regions of the world. Sizes range from about 1 m² to over 4 km², and occur alone or in clusters covering many square kilometers (Christy, 2012). More commonly, vernal pools are found in clusters, and are characterized by mound-depression microrelief landscapes (Dlugolecki, 2010).

Ecosystems in vernal pools are driven by their unique hydrology (Bauder, 2005; Clausnitzer and Huddleston, 2002). They develop in shallow depressions as seasonally perched water systems, on either impermeable bedrock or cemented calcareous or siliceous hardpan soil with a high clay content, limiting or stopping significant infiltration, and not having significant groundwater inflow or recharge (Christy, 2012; Clausnitzer and Huddleston, 2002; Cook and Hauer, 2007; Crowe et al. 2004; Zedler, 1987). The hydrology is characterized by four distinct annual phases: filling, ponding, drawdown and desiccation (Robins and Vollmar, 2002). After the pool substrate becomes saturated the depressions are filled, primarily via direct precipitation during the winter and spring, and secondarily by overland flow and shallow subsurface lateral flow, and are typically otherwise hydrologically isolated from other systems (Adamus and Field, 2001; Cook and Hauer, 2007; Williamson et al. 2005; Zedler, 2003). However, the degree and behavior of hydrological interaction with the subsurface layers, and hydrological connectivity to other vernal pools are variable, dependent on topography, soil and hardpan properties, distribution, timing and volume of
precipitation (Adamus, 2006; Cook and Hauer, 2007; Williamson et al. 2005). Regardless of the degree of hydrologic interaction, vernal pools are always “isolated wetlands” at least at some point of the year (Comer et al. 2005). The pools become desiccated from late spring to early fall primarily through evapotranspiration and secondarily through seepage (Adamus, 2006; Williamson et al. 2005; Zedler, 2003). The relative amount of loss from each of these pathways is dependent on the soil, geologic substrate, climate and local vegetation (Zedler, 2003). The duration of ponding typically lasts for a few weeks to a few months, depending on the water holding capacity of the soil, position in the landscape, precipitation and evapotranspiration rates (between and within years) and depth of the depression (Bauder, 2005; Robins and Vollmar, 2002).

Vernal pools, along with other small and isolated wetlands, are critical for maintaining regional biodiversity (Semlitsch and Bodie, 1998). Many ecologically unique traits are characteristic of them, which corresponds to highly specialized native, rare and/or endemic animal, plant (often annual) and macroinvertebrate habitation (Adamus, 2006, Bauder, 2005; Williamson et al. 2005; Zedler, 2003). The species that utilize vernal pools are the drivers for the ecological interactions that occur between the pools and the upland regions (Adamus, 2006). The reliable returning presence of water to a vernal pool bed is the defining character that allows specialized and unique biota to develop, and discourages upland plants from encroaching (Williamson et al. 2005; Zedler, 2003). There is variability in species compositions in vernal pools within relatively close spatial extents, due to the independent variable sizes of the pools (Zedler, 2003).

Water chemistry is also a crucial determinant of native species distribution and life history stages in vernal pools (Adamus, 2006). Plants and animals that rely on vernal pools must be able to deal with high interannual variation in the period of ponding, highly variable water levels (particularly during the rainy season), variable water chemistry, and hot air and soil temperatures with low moisture during the dry season (Bauder, 2005). The resulting biotas have a unique niche with a low tolerance to predation, and traits highly tolerant of extreme variability, such as capability to survive in both aquatic and terrestrial
habitats, and a life cycle that is completed within the wet phase (Robins and Vollmar, 2002; Zedler, 2003). Species evolution with regard to specialization and endemism occurs in vernal pools because of their isolated “island-like” habitats, such as with the many endemic species of fairy shrimp (*Anostraca*) that occur in vernal pools across the U.S. (Zedler, 2003). Because of the naturally low-predatory (fishless) environment of vernal pools, they are an important habitat for natal amphibian and insect species that otherwise would be at risk in permanent ponds (Compton et al. 2006; Zedler, 2003). In addition to rearing in the pools, some amphibians also range at least 300 m from the vernal pool depression for migrating, dispersing, foraging and hibernation (Oscarson and Calhoun, 2007).

Vernal pools are also known to be an important water source for wetland birds such as migrating, wintering or breeding waterfowl, raptors, songbirds, shorebirds, birds of prey, mammals, turtles and pollinating insects (Adamus, 2006; Tuss, 2013). A unique combination of macroinvertebrate species inhabit the water column and saturated substrate during the wet season, as well as the upland grasslands, which provide as a crucial food source for species higher on the food chain (Adamus, 2006; Tuss, 2013). As the vernal pool substrate dries out, it becomes a bank of insect and crustacean cysts and eggs and dormant plant seeds, which are released in the following wet season (Dlugolecki, 2010; Tuss, 2013). Different compositions of plants will emerge from vernal pool seed banks depending on the timing and intensity of precipitation, and as such they may contain seeds from rare and endangered species that have not germinated in decades (Bliss and Zedler, 1998; Deil, 2005). Plants inhabit the basin in rings as they dry (Tuss, 2013). The plant species distributions change along the elevation, moisture and salinity gradients of the basins, from more to less obligate species as they move outward, up to the bankfull elevation, and the locations of the plant gradients and communities vary annually based on the variable precipitation (Bauder, 2000; Bliss and Zedler, 1998; Dlugolecki, 2010). The wetland plant species that inhabit the vernal pools will vary also with duration of ponding. For example, facultative-wet or obligate plants will be more correlated with vernal pools with longer hydroperiods than shorter (Adamus,
Bliss and Zedler (1998) showed that vernal pool specific species tend to not germinate under un-favorable conditions (temperature and precipitation timing), and therefore may not be resilient to climate change, giving generalizing species a higher competition factor.

Vernal pools act as nutrient sinks and water purification systems with regard to nitrogen removal, phosphorus processing and pesticide and metal detoxification (Adamus, 2006). Vernal pools are also thought to be effective at removing pollution such as nitrogen from the air and shallow groundwater, through slow processing due to their isolated nature and aerobic-anaerobic cycle (Adamus, 2006).

The management of vernal pools is also highly variable. Vernal pools are managed for a wide range of things such as water sources for agriculture, livestock in rangeland, wildlife refuges and conservation. Due to their clay-rich substrate and use by sensitive species, they are easily affected by human activities, and they are threatened in many places globally (Deil, 2005).

### 1.4. Effects of Alterations to Vernal Pool Ecosystems

Vernal pools typically develop over a long period of time within a specific hydrologic and soil regime (Adamus, 2006). Many vernal pools are anthropogenically altered to control the hydrology while others are left in their natural geomorphic structure (Bauder, 1998; Bauder, 2005). A vernal pool is altered when the soil or hydrology is changed by an anthropogenic activity, such as compaction for vehicle passage, excavating, filling or puncturing the hardpan (e.g., via digging, blading, disking), or heavy grazing during the wet season that creates deep impressions from animals (Adamus, 2006; Bauder, 1988). These actions change the hydrology and topography in ways that are important to the species that use the pools and the overall function capacity of the pools (Adamus, 2006; Bauder, 1988).

Physical alteration of vernal pools alters habitats and species distributions, as naturally gentle slopes are converted to steep ones, causing sharp boundaries between microhabitats and moisture conditions, and disturbed soil profiles
(Bauder, 2005). This often leads to the favoring of certain species at the expense of others, and decreases the benefits of buffering effects of natural hydrological properties (Bauder, 2005). Species favored from alteration tend to be non-native invasives, which compete with and crowd out natives adapted to the natural hydrological regime (Adamus, 2006). Native wildlife are negatively impacted by this also, since they evolved with native plants (Adamus, 2006). Native vernal pool plants and animals are particularly sensitive to alterations of inundation patterns and water quality (Adamus, 2006). Vernal pools that have had soil compaction or partial drainage are thought to be less effective at processing contaminants and nutrients such as nitrogen, as these actions decrease the abundance and richness of beneficial microbes which are crucial to ecological processes (Adamus, 2006). The ecological benefits of vernal pools are greatest when the hydrology (depth and duration of ponding, precipitation frequency and timing) is that of an un-altered regime (Adamus, 2006).

Many times vernal pools are degraded because they lie in the path of suburban development, which often causes a loss of connectivity between vernal pools as they become filled and more spread out (Compton et al. 2006). Hydrologic connectivity can be an important driver of vernal pool water chemistry, biodiversity, vegetation structure and net primary productivity (Cook and Hauer, 2007). Loss of vernal pool connectivity and numbers equals a reduction of shoreline in the region, which is an important location for nutrient cycling processes (G. Waldbusser, personal communication, May 21, 2013). Loss of vernal pool connectivity can also lead to amphibian declines due to their pool and overland dispersal behaviors, and a decline in their connections to other populations (Compton et al. 2006; Semlitsch and Bodie, 1998). Therefore, their ability to withstand stochastic fluctuations is decreased, demonstrating the importance of looking at vernal pools on multiple scales (Compton et al. 2006; Oscarson and Calhoun, 2007).

The ways in which grazing alters vernal pool systems can be positive or negative, and is controversial. Robins and Vollmar (2002) stated that grazing changes vernal pool ecology in three primary ways: phytomass removal through
consumption of vegetation, trampling of vegetation, and nutrient input through excretion. They suggest that cows decrease the number of invasive species in vernal pool ecosystems (in the upland and in the vernal pool basin) through phytomass removal, and therefore increase the ability of native populations to compete. They argue that these functions are similar to those provided by historic natural wildfires and historic large native herbivores, and therefore keep the land closer to the natural regime. Other researchers have also supported the theory that grazing can remove harmful dry thatch caused by already existing invasives (Adamus, 2006). However, this may not be true in many of the semi-arid landscapes of the inter-mountain west, as they have evolved without large mammal herds, and therefore the regional bunchgrasses lack adaptations to resist this type of disturbance (Fernandez et al. 2008). Uncontrolled overgrazing in the mid-1800s up until the Taylor Grazing Act of 1934 is believed to have severely altered the ecosystems of the Northern Great Basin rangeland (Dlugolecki, 2010). Clausnitzer and Huddleston (2002) cite studies that demonstrate grazing, trampling and nutrient redistribution by livestock impact soils, vegetation, small vertebrates, invertebrates and microbial communities in uplands.

Croel and Kneitel (2011) studied effects of cattle waste on vernal pools and found that it increases orthophosphate, conductivity and turbidity, and decreases dissolved oxygen, bringing the vernal pool systems closer to a eutrophic state, and significantly reduces plant richness. They concluded that any benefits that may occur from grazing do so in the surrounding upland rather than inside the vernal pool basins.

Alteration of vernal pool topographies and hydrology in grazing areas is detrimental, and this does not appear to be disputed in the available literature. Anthropogenic changes are very common, particularly by partial excavation to lengthen the duration of water ponding and to act as a stock pond (Clausnitzer and Huddleston, 2002). Another topographical alteration from livestock occurs from deep hoof impressions into the soil profile when livestock walks across the basin when it’s wet.
(Adamus, 2006). The establishment of aquatic plants could encourage proliferation of predaceous aquatic insects that reduce tadpole survival, reduce or eliminate fairy shrimp populations which affects animals that prey on them such as wading birds, and reduce the surface area suitable for growth of vernal pool forbs (Clausnitzer, 2000; Clausnitzer and Huddleston, 2002; Graham, 1997; Roth and Jackson, 1987; Weir, 1971). Euliss and Mushet (2004) found excavations in wetlands in a semi-arid landscape caused increased salt concentrations and decreased vegetative structure, which negatively impacted native macroinvertebrates, amphibian and plant communities. Increased ponding duration could also lead to increased range of large herbivores (livestock and native) later into the year, into areas they would typically not go due to lack of water (Clausnitzer and Huddleston, 2002; Landsberg et al. 1997).

1.5. Vernal Pool Regulation

Typically, vernal pools in most areas are not specifically or inherently protected by wetland regulations as they do not meet legal thresholds such as for soils, vegetation and hydrology (D. Field, personal communication, March 5, 2013). In addition, although the use of the term “vernal pool” has become more consistent in recent decades, it is still sometimes incorrectly over-used to include ephemeral wetlands that do not undergo extreme desiccation in most years, and they are difficult to delineate and classify due to their high hydrologic variability (Comer et al. 2005; Ruffolo, 2002; Zedler, 2003). Clausnitzer and Huddleston (2002) state that it has been difficult to give vernal pools federal wetland status because of their highly seasonal hydrology, indistinct hydric soil indicators, small ephemeral wet-season plants, and in Oregon’s high desert, ambiguity about the sub-species and wetland status of the dominant shrub. They emphasize the importance of evaluating vernal pools during their wet season to accurately determine their wetland status.
Whether Section 404 of the Clean Water Act (CWA) protects wetlands has been highly controversial, but Section 404 did end up giving some regulatory protection specifically to vernal pools in litigation cases won in 1985 through 1988 (Ruffolo, 2002; Zedler, 2003). Most vernal pools lost this protection in 2001 (although some of the larger pools were not affected), when the U.S. Supreme Court ruled that non-navigable “isolated wetlands” are not allowed the same federal protection as year-round wetlands offered by the CWA, further increasing risk of vernal pool loss and leaving regulation up to the states (known as the SWANCC decision) (Comer et al. 2005; P. Adamus, personal communication, March 21, 2013; Ruffolo, 2002).

Despite the difficulties, protections for vernal pools are slowly increasing, most commonly through the Endangered Species Act (ESA) due to the discovery of listed species existing in them. For example, the vernal pool fairy shrimp (*Branchinecta lynchi*) has brought protection to some of southern Oregon’s vernal pools (in Agate Desert and Table Rocks) due to listing as a federally threatened species, along with some rare plants (Adamus, 2006; C. Tuss, personal communication, March 4, 2013). The Migratory Bird Act, the Fish and Wildlife Coordination Act, the Land Use and Water Conservation Fund Act, and the National Environmental Policy Act all have also provide limited protection to vernal pools if they meet various defined criteria (Ruffolo, 2002). Even if a vernal pool is eligible for protection, research must be conducted and demonstrate that it meets eligibility requirements before protection. If there are no threatened or endangered species in a system, federal agencies such as the Fish and Wildlife service are generally limited to recommendations for minimizing harmful impacts (Ruffolo, 2002).

Local governments often play a vital role in giving some protection to regional vernal pools through local regulations and ordinances (Oscarson and Calhoun, 2007). Additional protection of vernal pools can come from agricultural incentive programs, conservation programs and state regulations, although about two thirds of states had not enacted protection as of 2005 (Comer et al. 2005). Many researchers believe protection that does exist in some areas still does not
adequately protect the ecosystem functions and species vernal pools support, as an adequate amount of area around vernal pools are not included, and connectivity is not considered (e.g., Oscarson and Calhoun, 2007; Semlitsch and Bodie, 1998).

1.6. Existing Data on Oregon’s High Desert Vernal Pools

Most research on and classification of vernal pools in the west has been conducted in central to south western California, where they have been shown to be highly variable (e.g., Bauder, 2000; Bauder, 2005; Butterwick, 1998; Holland, 1998; Keeler-Wolf et al., 1998; Robins and Vollmar, 2002; Ruffolo, 2002; Williamson et al. 2005; Zedler, 1987). Additionally, of the research that has been done on Oregon’s vernal pools, most have been in western Oregon in very different ecological regimes than the high desert (e.g., Adamus, 2006, Tuss, 2013). It is likely that Oregon’s high desert vernal pools differ even more from the standard understanding of vernal pools as described in existing research. Due to the extreme variability of vernal pools, it is important to summarize what is known about them regionally.

The area of interest includes vernal pool sites from Deschutes, Lake and Harney counties (primarily in Lake), spanning across Central to Eastern Oregon, and South to near the Nevada border (Figure 1). The region is a semi-arid high desert, shrub-steppe community that lies across the Northwestern Great Basin and High Lava Plains. Human inhabitation is sparse. Surface hydrology is closed drainage system so all of the surface water evapotranspirates or percolates without reaching the ocean (Dlugolecki, 2010). Vernal pool hydrology is controlled by the distinct cool and wet winters, then hot and dry summers where they occur (Bauder, 2005; Clausnitzer and Huddleston, 2002). Vernal pools in the area occur in shallow depressions where often inconspicuous vegetation grows for just part of the year (Clausnitzer, 2000). Natural pools in the region have no obvious alterations, and are typically shallow and ponded on a flat basin (Figure 2). Altered pools often contain an excavated dugout within a section of the natural basin, or a bermed wall to increase water retention (Figure
The majority of the pools are open to cattle, except in the Hart Mountain National Antelope Refuge where cows are currently excluded. In addition to the pools, cattle also have access to metal guzzlers fed by pumped groundwater and excavated dugouts in random locations (not inside vernal pool basins.)

Figure 1. Location of Study Area Containing Vernal Pools
Figure 2. Natural Basins. Photographs by author.
Figure 3. Altered Basins. Photographs by author.
The semi-arid climate of the area has long, severe winters and short, dry and hot summers. Specific temperature and precipitation are spatially and temporally variable, in part due to the high intensity, low range storms that occur in the high desert. Great fluctuations between drought and high precipitation often occur (Dlugolecki, 2010). In the Hart Mountain Antelope Refuge, January temperatures range from -16 to 9.7 °C on average, and July temperatures range from 9.2 to 28.3 °C on average (Western Regional Climate Center, 2013). Precipitation is usually 150 to 300 mm per year, with most of that falling as snow from November through March, then as rain from March through May (Western Regional Climate Center, 2013).

Most vernal pools in the study area appear very hydrologically isolated from each other, as they were noted to occur sporadically and considerably far apart, with the exception of the Warner Valley Wetlands at the base of Hart Mountain. The area consists of a distinct mosaic of small and large wetlands where the surface water is clearly connected in the wet part of the year. As the season dries, the pools shrink and the surface water disconnects, and the pools dry out in order of smallest to largest size. The largest of the ponds do not completely dry out in most years, and are therefore are considered year-round wetlands rather than vernal pools.

Clausnitzer (2000) and Clausnitzer and Huddleston (2002) conducted a three year study of a vernal pool within our study area in northern Harney County of standard wetland criteria for a vernal pool (hydrology, soils and vegetation) to determine its jurisdictional classification. Installed groundwater monitoring piezometers between 5 and 100 cm depths at two points (upland and wetland) within a vernal pool depression demonstrated the water was perched above a very shallow, slowly permeable Bt horizon above 25 cm. The results indicate extremely shallow soil saturation (i.e., perched system), very little percolation, with no connectivity to groundwater or subsurface lateral flow. The hydrology in the vernal pool studied was completely controlled by direct precipitation and nearby overland flow, and lost almost completely by evapotranspiration in
warmer months. Minimal percolation was assumed to occur, allowing salts to be transported into the soils as evidenced by low saline levels in the pool, presence of fine plant roots, and downward increases in fine clay, dissolved CaCO₃, soluble salts and exchangeable cations. Refer to Clausnitzer (2000) for many more data on water chemistry, soil chemistry, and vegetation of the vernal pool in the study area.

In the Clausnitzer (2000) and Clausnitzer and Huddleston (2002) study, ponding occurred from early January to mid-April, with brief refilling from later spring precipitation. The data show the overlap of ponding during the growing season was sufficient to meet the hydrology criteria for a wetland, and vegetation consisted of dominating facultative or obligate wetland plants. The soils were determined to be hydric based on the wet season hydrology, redox potential data demonstrating anaerobic conditions at 5 to 100 cm depth during the wet season, and soil temperature above biological zero (5 °C in the upper zone) during saturation, indicating a growing season. The soils would not have been classified as hydric under standard indicators, and therefore they recommended further consideration for inclusion of additional indicators that help identify vernal pool wetlands. They determined the soils and vegetation meet the federal definitions for wetland classification, and stressed that vernal pools must be evaluated during the wet season for proper determination of eligibility.

Most vernal pool soils have a high clay content. Crowe et al. (2004) found that the vernal pools in Eastern Oregon have vertisol soils, having a clay content >30%. This is supported by the distinctive shrink-swell characteristics observed during the 2011 and 2012 field visits (Figure 4). In the Clausnitzer (2000) and Clausnitzer and Huddleston (2002) study, they found clay contents in the Bt horizon to be 50 to 82% in two spots (one sandy loam and one silt loam) in the basin. The soils have relatively low iron due to parent materials, relatively low organic matter due to low biomass production, low redoximorphic features due to low carbon levels and small amounts of iron and manganese, and high pH due to evaporative accumulation of salts (Clausnitzer, 2000).
Figure 4. Desiccated and drying vernal pool beds in Eastern Oregon demonstrating shrink-swell characteristics typical for high clay-content vertisol soils. Photographs by author.
The growing season in Harney County is from early April through October (Taylor, 2013). In the northwestern Great Basin, soil moisture is typically depleted by mid-summer, inducing dormancy in most plants (Clausnitzer, 2000). Vernal pool plants inventoried in the northwestern portion of the study area are dominated by forbs, and secondarily by grasses (Dlugolecki, 2010). Shrubbery such as Silver sagebrush (*Artemisia cana*) typically exist along the outer portions on the vernal pool beds, but not in the middle where the longest duration of ponding occurs (Clausnitzer, 2000; personal observations).

Fauna species seen using vernal pools in the study area include the greater sage grouse (*Centrocercus urophasianus*), migratory birds such as the long billed curlew (*Numenius americanus*) and the double-crested cormorant (*Phalacrocorax auritus*) (Dlugolecki, 2010). In a relatively small scale study conducted on vernal pools in the northwestern portion of our study area, a species inventory was conducted where they found 159 vascular plant species in 70 pools, 51 bird species in 59 pools, 13 non-bat mammal species in 57 pools, 12 bat species in 15 pools and 62 species of aquatic macro-invertebrates in 30 pools, with reason to believe the actual number of species present was much higher (Dlugolecki, 2010). The species rarity was analyzed and found to be high (Dlugolecki, 2010). Non-cattle fauna or their scat observed at vernal pools during 2011 through 2012 field visits include pronghorn, greater sage grouse, coyote, various frogs, bats, black tailed jack rabbits, killdeer, ducks, geese, various songbirds, beetles, and macroinvertebrates. The vernal pool study also determined the vernal pools failed to meet the standards and guidelines of rangeland health (Dlugolecki, 2010).

The only existing water quality samples taken in the region was by the BLM Prineville District, for water rights allocation purposes. Parameters measured were limited to conductivity, temperature, and pH, and were regarded as “passing” when applied to the Oregon Department of Environmental Quality (ODEQ) section 303(d) for impaired waterways as a reference for standards, because no standards exist specifically for vernal pools (Michelle McSwain and Jenny Mofitt, Prineville BLM, personal communication). Macroinvertebrate
sampling was also done by BLM at multiple altered and un-altered vernal pools; the highest macroinvertebrate diversity was recorded at an un-altered pool.

Surface water systems in Oregon’s high desert have been extensively mapped, including vernal pools. Most of the larger vernal pools in Oregon’s high desert are mapped on high resolution road atlases, many of them named with a “Lake” or “Watering Hole” ending. The pools are completely mapped and classified in the NWI based on stereoscopic analysis of high-altitude aerial photographs (Clausnitzer and Huddleston, 2002). The classification system seems to adequately classify vernal pools as temporarily or seasonally flooded, and often includes an alteration indicator when a dugout or berm exists in the basin. However, the NWI classification system is limited to a general classification and has been known to contain misclassifications.

Comer et al. (2005) conducted a broad study on the existence of isolated wetlands in the U.S., with Oregon as one of the states focused on. According to them, most of Oregon’s isolated wetlands exist in Lake and Harney counties, and were classified to be Inter-Mountain Basins Playa and North Pacific Hardpan Vernal Pools. They identified 422 isolated wetlands in Harney county, with one G1 (“critically imperiled”) to G3 species closely associated with isolated wetlands, and 299 isolated wetlands in Lake county, with 9 G1 to G3 species closely associated with isolated wetlands. This is likely low, in part due to a strict definition of “isolated”, and the existing data they used was incomplete. Also, it is important to understand that the category of isolated wetlands includes systems other than just vernal pools (Ruffolo, 2002). The way in which this study is useful for looking at vernal pools specifically is unclear other than the general observations made about the area. They determined that Oregon’s isolated wetlands are unique in that the majority of them are on public land rather than private. Therefore, more opportunity for research and protection exists than on private lands. The study was based on existing data that was generally limited to a more gross scale than desired for wetland assessment, and did not go into further detail about the region.
Despite the level of mapping water systems in the area have received, to our knowledge a specific, broad and comprehensive inventory of vernal pools in Oregon’s high desert has not yet been performed, and therefore the total quantity is unknown and usually very roughly estimated when discussed. Additionally, comprehensive studies involving temporal water change and availability in the area do not seem to exist. Fortunately, remote sensing of the vernal pools is not limited in the region by obstructions other than clouds, as the tree cover density is extremely low. The ephemeral nature of vernal pools makes remote sensing trickier than it would be for perennial systems. Despite this, remote sensing techniques have been utilized to identify and evaluate vernal pools in the U.S, most often with aerial imagery photointerpretation, (e.g., Compton et al. 2006; Lathrop et al. 2005; Oscarson and Calhoun, 2007). However, these techniques have not been applied to evaluate vernal pools in the region.

Much of the landscape that Oregon’s high desert vernal pools exist on is heavily used for livestock grazing, other than inside of the Hart Mountain National Antelope Refuge where they have been excluded since 1990 for a 15 year rest period. The extent of effects grazing has had on the communities in the region is unclear, although they are believed to be negatively altered (Dlugolecki, 2010). Primary observed topographical alterations to vernal pools consist of a bulldozed hole inside the basin with fill berms piled up on either side (referred to as a dugout), or a single bermed side of a basin to hold water in longer (Figure 3). During the late winter and early spring, water often exists in the dugout and in the surrounding basin (i.e., the dugout is “overflowing”, in a sense). As the water evapotranspirates, the unaltered portion of the basin dries first, and water remains only in the altered dugout for much longer.

The BLM created the dugouts in most of the larger vernal pools primarily between 1950 and 1970 to increase water yield later into the year for livestock and wildlife, although they do not dig them on public land anymore (Dlugolecki, 2010). There is a growing concern that the alteration of hydrology is affecting native vernal pool habitat by causing
the larger portion of the basin outside of the dugout to hold water for less time, changing the soil moisture across the basin (Reuter et al. 2013). In 2008, the BLM Prineville District filled several dugouts in the study area with the surrounding berm material in order to restore the natural topography and hydrology, and created a five acre cattle exclusion area around them (Dlugolecki, 2010). Whether or not this will restore natural vegetation and positively impact fauna species is yet to be determined (Dlugolecki, 2010). Field visits in the study area confirmed that water remained considerably longer in the altered portions of the basin than in the natural areas, or in natural basins nearby. Additional topographic alterations from livestock in the area occur from cattle walking around in the basins while the clay substrate is wet, leaving deep impressions that dry and remain until the following year (Figure 5).
Many states have implemented vernal pool protection, although none as stringent as would be provided by the CWA if vernal pools were covered. In Oregon, the Oregon Removal-Fill law (ORS 196.795-990) prohibits excavation or fill of waters including wetlands, but only if the alteration is larger than 38.2 m$^3$. Whether or not this protects Oregon’s vernal pools is unclear. Agencies such as the BLM, the United States Forest Service (USFS), Oregon Department of Fish
and Wildlife (ODFW) and ODEQ are implementing restoration projects on vernal pools, yet there is not a clear understanding of what differentiates an altered and unaltered vernal pool (Dlugolecki, 2010). These agencies are interested in quantifying the ecological status of vernal pools, and the ecological benefits of restoring them to their natural state. In many situations, restoration of vernal pools could conflict with the use for grazing (Dlugolecki, 2010).

1.7. Preliminary Analysis of NWI Data

A preliminary GIS analysis was conducted to analyze the feasibility of using NWI data to identify the number, locations and level of alteration of vernal pools in the region. The first issue is NWI drew palustrine wetland polygons around dry basins that do not pond water during most years. Dry basins were evaluated for NWI classification to illustrate this issue. Basins that are likely dry were identified by several factors. On June 14, 2011, the study area was flown over, and notes were taken of presence/absence of ponded water in previously identified natural basins. Since fall 2010 through spring 2011 were unusually high precipitation times, much of the general area was flooded (i.e., many sections of high desert ground outside of basins had ponded water). Even so, some of the basins targeted were witnessed to be dry at that time. Landsat Multispectral (MSS) imagery of several of the basins noted to be dry at that time were evaluated for presence of water during wet times of February through May of several years, and water was never found to pond in them. The basins may still be wetlands if temporary subsurface saturation is occurring, and direct long-term observations would need to occur to definitely conclude whether or not they are wetlands. However, lack of ponding during regional flooding times is evident the basins do not conform to typical wetlands in the region. However, NWI still has these basins coded as occasionally flooded palustrine wetlands (Figure 6), which is the same classification given to many of the surrounding basins.
that were confirmed to regularly hold water. Although this situation is relatively rare compared the total number of basins in the area (mainly because almost all of the basins that exist in the area actually do hold water), it illustrates the inability to use NWI to identify historic basins that don’t hold water anymore.

Figure 6. Cluster of Dry Basins Classified in NWI the Same Way as Vernal Pools in the Area.

The NWI classification coded these dry basins as Palustrine Shrub-Scrub regime that is intermittently flooded (PSSJ), Palustrine Unconsolidated Shore that is seasonally flooded and excavated (PUSCx), and Palustrine Unconsolidated Shore that is intermittently flooded (PUSJ).

A GIS analysis was performed on NWI data available for Harney and Lake Counties to get a sense of the number of vernal pools that exist, and how many of them are altered. Vernal pools are expected to be classified as palustrine, with a wide diversity of the type of palustrine wetlands (Cowardin et al. 1992; Ferrin et al. 1995). The GIS analysis removed all wetland polygons other

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1 Refer to Appendix for details on the GIS analyses.
than palustrine (lake and riverine), and removed all wetlands coded to be permanently or artificially flooded. The resulting palustrine wetland polygons are 17,919 in Harney County, and 27,596 in Lake County. Of these, 3,471 in Harney County (15%) and 3,485 in Lake County (13%) were coded as altered by diked/impounded, partially drained/ditched, artificial, spoil or excavated. However, spot checks demonstrated that some field verified vernal pools were coded as lakes in NWI and therefore were removed from this number, and many remaining palustrine wetlands are long, thin polygons that would more likely to be considered ephemeral creeks than vernal pools. The NWI classification system has no further distinction between these and vernal pools (i.e., the classification codes are identical between the two types in this area), so the exact number cannot be determined with this data.

The reasons for these NWI results are easier to understand when taking a closer look at the NWI data. The data tend to break up one system into many polygons, often with different classification codes. This is demonstrated when looking at how NWI classified one vernal pool that was repeatedly visited in 2011 through 2012² (Figure 7). The alteration regime shown is typical in vernal pools in the study area (dugout inside a basin). Using the ideology that vernal pools should be classified as palustrine, the NWI data would show two vernal pools here, both along the outer ring of the depression. Neither method of limiting NWI data to classifications typical of vernal pools would include the two inner polygons, as they are both coded lacustrine. Additionally, the NWI data show this single system as four polygons, and only one of them have an altered designation (the dugout hole itself is considered a separate wetland, and is the only one considered altered). For the purposes of our studies, this system would be counted as a single altered vernal pool. Classification of each portion of the vernal pool separately such as shown here is the norm in the NWI data. Therefore, if you looked at each vernal pool as a single site, the percent of vernal pool systems that are altered are much higher than estimated using the NWI analyses, and the total number of vernal pools is much lower than estimated.

² Vernal pool located at 120° 32’ 15"W, 43° 34’ 48"N.
On-site and Google Earth observations of hundreds of Oregon’s high desert vernal pools supports the theory that alteration of the topography exists in a much higher proportion than would be estimated based on NWI classification polygons.

![Image of the NWI Classification of an Oregon High Desert Vernal Pool](image)

**Figure 7. NWI Classification of an Oregon High Desert Vernal Pool.** Vernal pool visited during the 2011 through 2012 field visits (left), and the associated NWI classification (right). The NWI classification coded the outer ring as palustrine shrub-scrub regime that is temporary flooded, the main section of the basin as lacustrine littoral unconsolidated shore that is seasonally flooded, and the dugout portion of the basin as lacustrine littoral unconsolidated shore that is semi-permanently flooded, with an excavated identifier (x).

A GIS analyses was developed to rectify the issues. All NWI polygons that intersected with the study area were selected, and all riverine polygons and lakes greater than 28.3 km$^2$ were removed (Figure 8).
Figure 8. Topographic Image of Study Area (Left), Polygon Boundary of Study Area (Middle), and Resulting NWI Pool Polygons following GIS Processing (Right).
The remaining polygons were those classified as palustrine or lacustrine, and were smaller than 28.3 km². The Dissolve tool in ArcGIS 10 was used to merge the remaining polygons that had adjoining boundaries, so each hydrologic system would be represented as just one polygon (Figure 9).

![Figure 9. Result of Dissolving NWI Polygons to Achieve One Polygon for One Hydrologic System. Polygon is of the same system as shown in Figure 8.](image)

The resulting polygon layer represents the number of isolated wetlands in the study area. The number of these that are altered was determined by extracting the dugout polygons from the un-dissolved layer (polygons with an alteration symbol such as excavated (x) at the end). The resulting quantity of altered polygons in the study area is 2,003, and the resulting quantity of isolated pools in the study area is 4,202. Therefore, the overall percent of alteration in the study area is 48%. Approximately 600 of the isolated pools occur in three compact mosaic
clusters in the Rock Creek Drainage, the Warner Valley Wetlands, and the western flank of Harney Lake. Here, the proportions of altered pools are much lower than in the regions where the pools are more isolated. Therefore, the percent of alteration is higher and lower depending on the sub-region within the study area. The method could be altered to analyze narrower regions to get a better idea of vernal pool conditions in specific areas. Since NWI classifications do not properly differentiate vernal pools from other systems in the area, further differentiation cannot easily be done with this data alone. Local data on vernal pools could help further narrow the results to exclude other systems, such as the approximate maximum size of vernal pools that exist in the region. Additional data sets such as soils and the National Hydrography Dataset (NHD) could further augment the identification process. Although this method includes some non-vernal pool systems in the area, it is an effective way to get a sense of the number of vernal pools, and level of alteration that exists in them.

1.8. Summary

Vernal pools in Oregon’s high desert represent a unique ecology that is different to those of other regions. For example, they are not as wet and lush as California’s vernal pools described in the literature. The importance of their ecological functions has likely been underemphasized, as they have been under studied, and they provide unique vegetation and hydrology that contrast sharply with the uplands, in an otherwise semi-arid region (Clausnitzer, 2000). Many wildlife rely on them for provision of provide food and water, including pronghorn, sage grouse and wading birds, act as breeding grounds for local amphibians, and play other important roles in the surrounding ecosystem (Clausnitzer, 2000). Many of them are in year round sage grouse habitat, which is a candidate for the ESA (Dlugolecki, 2010). Pacific Flyway migratory birds depend on them for nesting, feeding and resting grounds (Dlugolecki, 2010). The pools create islands of biodiversity in otherwise somewhat barren landscape, and are critical
for the survival of many species that exist in the region. Beyond general facts, little detail is known about the full range of plants and animals that utilize them (Clausnitzer, 2000).

Loss of vernal pools is concerning because it also means loss of rare, endemic species that depend on them (Comer et al. 2005). Several studies have estimated that more than 90% of California’s vernal pools had been destroyed, mostly prior to the CWA, primarily from agricultural and urban development, dredge or fill material discharge, and grazing, and the majority of remaining pools are severely altered (Ruffolo, 2002; Zedler, 2003). Even so, the remaining vernal pools still play a vital role in maintaining the state’s biodiversity, due to high proportion of rare species that exist in them (Ruffolo, 2002).

When deciding whether or not to restore a vernal pool, managers should conduct a comprehensive vernal pool assessment, using a standardized method such as the Functional Assessment Methodology (Adamus, 2006), or the Hydrogeomorphic Model Approach (Butterwick, 1998), tailored to the region of interest. The value of vernal pools in maintaining native wildlife is greater in areas where there are not many other wetlands and where pools are not numerous (Adamus, 2006), as is the case in much of Oregon’s high desert. Agencies that are implementing restoration projects on vernal pools do not yet have a clear understanding of the specific benefits of doing so, including changes that might occur in water quality (Dlugolecki, 2010). Given the risk of loss of biodiversity, species extinction, and overall ecosystem function, the need for a more complete understanding of Oregon’s high desert vernal pools is high. Although Clausnitzer (2000) conducted an in depth three year study of a vernal pool in the study area, he emphasized the need for broad range studies across the area to account for vernal pool variability.

Most research supports the theory that moderate cattle grazing in the uplands of vernal pools can have positive impacts on retaining diverse native vegetation in vernal pool ecosystems, as long as alterations such as excavation and fill are not also occurring. However, it may not hold true in Oregon’s high desert as sensitive plant species may not have evolved to handle large ungulate
Livestock inside wet vernal pools creates deep impressions and excretion input can potentially negatively alter the water chemistry, and most of at least the large basins have been excavated. It is hypothesized that the excavations have already changed the plant communities in the basins, and long-term overgrazing prior to the Taylor Grazing Act of 1934 significantly changed the ecosystems (Dlugolecki, 2010). Excavation holes in the vernal pool basins can have a number of impacts, including prolonging the ponding duration, establishment of fully aquatic plants, proliferation of predaceous aquatic insects that affect tadpole survival, reduce or eliminate fairy shrimp, and reduce vernal pool forbs that are an important food source to pregnant and lactating pronghorns and sage grouse and their broods (Clausnitzer, 2000; USDI – BLM and USFWS, 1998). The extent of impact these changes can have on Oregon high desert vernal pool ecosystems is unknown (Clausnitzer, 2000). Since it is not likely that grazing Oregon’s high desert vernal pools will end in the near future, managers can attempt to minimize negative impacts of cattle by applying the regionally appropriate grazing intensities to areas with vernal pools with conservation in mind. Since the majority of Oregon’s high desert vernal pools are located on BLM land, managing with conservation in mind should be easier than in most areas. Conservation-minded grazing on private land can be encouraged with mutually beneficial conservation easement agreements (Robins and Vollmar, 2002). Time may show that removal of berms and fill of dugouts restores the hydrology, native sensitive vegetation and animal species back to the systems. If so, managers can select systems across Oregon’s high desert to apply the same restoration to, based on accessibility and minimal livestock conflict. Additionally, managers can install watering troughs for livestock to use as an alternative to the pools to reduce livestock impact.

Although the vernal pools in eastern Oregon are extensively mapped, they are generally called lakes and water holes on high resolution atlases, and the NWI classification system does not adequately differentiate vernal pools from other systems in the region. Very little baseline information exists on the hydrology, biodiversity, ecological functions, and restoration actions on Oregon’s
Therefore, it is not understood what stands to be lost if they are not protected from further degradation from grazing, development or climate change. The need for resolute descriptions and definitions of vernal pools in Oregon’s high desert is great, as is mapping specifically for them so that they may be properly accounted for, managed and protected. In addition to a comprehensive inventory, scientific analysis of water quantity change in Oregon’s high desert over time also does not seem to exist. Since vernal pools act as a water source for a relatively much more limited time than most, an understanding of overall water availability and change can aid managers in making informed decisions. The development of proper remote sensing techniques of Oregon’s high desert vernal pools can give managers a profoundly simpler method for determining how much water availability exists in the extremely rural areas, and monitor vernal pools’ change.

The existing data on Oregon’s vernal pools summarized above demonstrates the need for more research. Although some research has been conducted, a systematic inventory or a comprehensive study of ecological functions have not been conducted, and standardized management strategies have not been developed for the area. Vernal pools in California and New Jersey have been studied more completely, but there has yet to be comprehensive water quality or remote sensing studies of Oregon’s high desert vernal pools.

NWI data can be analyzed using the GIS method described, to get quick and reliable information on the number of isolated wetlands and level of alteration. The main limitation of the method is that it does not differentiate vernal pools from other types of nearby isolated wetlands, but assumptions can be made from the results knowledge of local vernal pools exists.

1.9. Study Purpose

Water quality data on Oregon’s high desert vernal pools were collected during the 2011 and 2012 field seasons. The purpose of the visits was to
develop baseline water quality data on a broad spatial range and type of vernal pools in the study area, and to see if there is a clear difference with respect to water quality between pools that are altered, those that are natural, and metal guzzlers. General characterizations of the vernal pools and the species that utilize them were also documented. In order to get an understanding of how the water quantity changes throughout a season, a GIS method was developed to quantify vernal pool surface areas from SPOT satellite images. Temporal change of vernal pool surface areas was also compared to climate data to see if clear correlations can be drawn.
1.10. References


WATER QUALITY OF OREGON’S HIGH DESERT VERNAL POOLS

Sara A. Wyland
2. WATER QUALITY OF OREGON’S HIGH DESERT VERNAL POOLS

2.1. Abstract

Vernal pools are surface water wetlands that undergo an annual cycle of filling, ponding, drying, and desiccation. They are typically isolated micro-regions of high biodiversity, including many rare and specialized species. Water chemistry during ponding determines the suitability of the water columns to support life, and is highly variable with fluctuating water quantity. Water quality analyses in Oregon’s high desert have primarily been limited to large lakes, and display extreme variability and low predictability. The purpose of this study was to develop baseline information on the general water quality of vernal pools with varying levels of topographical and hydrological alteration, across a broad range in Oregon’s high desert. Water quality was measured using a multiparameter water quality logger sonde and ion chromatography during 2011 and 2012. Sites were classified into natural, altered, dugouts inside basins, dugouts outside basins, and metal guzzlers. Sites were also classified into cow exclusion vs. cow inclusion zones. Temporal analysis of water quality data was evaluated for sites that were sampled more than once. Although some trends in site classifications were shown, the data were highly variable between individual sites of the same type. General temporal trends of pools showed increases in temperature, turbidity, conductivity and anions, and decreases in dissolved oxygen and oxidation-reduction potential throughout the seasons. Metal guzzlers displayed no temporal trends. Natural pools displayed opposite temporal trends of turbidity and nitrate than other site types, indicating different chemical functioning. Guzzlers compared to the pools had dramatically lower turbidity, lower temperature and phosphate, and higher conductivity, pH, nitrate and sulfate. Dugouts inside and outside basins had higher turbidity than altered and natural basins, indicating a potential impact excavated topography has on water quality. High variability exists in the data, even within site types. Although some patterns can be recognized, the data suggest little can be assumed about the water quality status of Oregon’s high desert vernal pools.
Abbreviations: ORP: Oxidation-Reduction Potential; DO: Dissolved Oxygen; ODEQ: Oregon Department of Environmental Quality; IC: Ion Chromatography; [H+]: Hydrogen Ion Concentration.

2.2. Introduction

Vernal pools are stagnant lentic surface water depressional wetlands which fill in winter months, dry out by the late summer in most years, and often dry out and refill several times in one year (Cook and Hauer, 2007; Clausnitzer and Huddleston, 2002; Tiner, 2003; Zedler, 2003). They develop in shallow depressions as seasonally perched water systems, on either impermeable bedrock or cemented calcareous or siliceous hardpan soil with a high clay content, limiting or stopping significant infiltration, and not having significant groundwater inflow or recharge (Christy, 2012; Clausnitzer and Huddleston, 2002; Cook and Hauer, 2007; Crowe et al. 2004; Zedler, 1987). The hydrology is primarily controlled by direct precipitation and evaporation, and is characterized by four distinct annual phases: filling, ponding, drawdown and desiccation (Robins and Vollmar, 2002).

Ecosystems in vernal pools are driven by their unique hydrology (Bauder, 2005; Clausnitzer and Huddleston, 2002). Vernal pools, along with other small and isolated wetlands, are critical for maintaining regional biodiversity (Semlitsch and Bodie, 1998). Many ecologically unique traits are characteristic of them, which corresponds to highly specialized native, rare and/or endemic animal, plant (often annual) and macroinvertebrate habitation (Adamus, 2006, Bauder, 2005; Williamson et al. 2005; Zedler, 2003). As the vernal pool substrate dries out, it becomes a bank of insect and crustacean cysts and eggs and dormant plant seeds, which are released in the following wet season (Dlugolecki, 2010; Tuss, 2013). Bliss and Zedler (1998) showed that vernal pool specific species tend to not germinate under un-favorable temperature and precipitation timing.

Vernal pools are also known to be an important water source for turtles, wetland birds such as migrating, wintering or breeding waterfowl, raptors,
songbirds, shorebirds, birds of prey, mammals and pollinating insects (Adamus, 2006; Tuss, 2013).

Many vernal pools are anthropogenically altered to control the hydrology while others are left in their natural geomorphic structure (Bauder, 1998; Bauder, 2005). A vernal pool is altered when the soil or hydrology is changed by an anthropogenic activity, such as compaction for vehicle passage, excavating, filling or puncturing the hardpan (e.g., via digging, blading, disking), or heavy grazing during the wet season that creates deep impressions from animals (Adamus, 2006; Bauder, 1988). These actions change the hydrology and topography in ways that are important to the species that use the pools and the overall function capacity of the pools (Adamus, 2006; Bauder, 1988). Euliss and Mushet (2004) found excavations in wetlands in a semi-arid landscape caused increased salt concentrations and decreased vegetative structure, which negatively impacted native macroinvertebrates, amphibian and plant communities.

The ways in which grazing alters vernal pool systems can be positive or negative, and is controversial. Robins and Vollmar (2002) stated that grazing changes vernal pool ecology in three primary ways: phytomass removal through consumption of vegetation, trampling of vegetation, and nutrient input through excretion. Croel and Kneitel (2011) studied effects of cattle waste on vernal pools and found that it increases orthophosphate, conductivity and turbidity, and decreases dissolved oxygen, bringing the vernal pool systems closer to a eutrophic state, and significantly reduces plant richness. They concluded that any benefits that may occur from grazing do so in the surrounding upland rather than inside the vernal pool basins.

Water chemistry is a crucial determinant of native species distribution and life history stages in vernal pools (Adamus, 2006). Plants and animals that rely on vernal pools must be able to deal with high interannual variation in the period of ponding, highly variable water levels (particularly during the rainy season), variable water quality parameters, and hot air and soil temperatures with low moisture during the dry season (Bauder, 2005).
Vernal pools act as nutrient sinks and water purification systems with regard to nitrogen removal, phosphorus processing and pesticide and metal detoxification (Adamus, 2006). Vernal pools are also thought to be effective at removing pollution such as nitrogen from the air and shallow groundwater, through slow processing due to their isolated nature and aerobic-anaerobic cycle (Adamus, 2006). Water chemistry analyses provide in depth insight into the suitability of the hydrologic system to support life.

2.3. Water Chemistry Overview

A complete water chemistry profile of surface water includes information on dissolved major ions (SO$_4^{2-}$, Cl$^-$, HCO$_3^-$, Ca$^+$, Na$^+$, Mg$^{2+}$, and K$^+$), dissolved nutrients (nitrogen, phosphorous and silicon), suspended organic and inorganic materials, gasses (N$_2$, CO$_2$, and O$_2$), and trace metals. A complete water chemistry profile is not always warranted for evaluating the water quality of a system, and often times a subset of these parameters is measured. Key water parameters often used in analyzing the water quality of freshwater systems include temperature, conductivity, pH, oxidation-reduction potential (ORP), turbidity, dissolved oxygen (DO or O$_2$), nitrate (NO$_3^-$) and phosphate (PO$_4^{3-}$).

Water temperature controls the rate of metabolic and reproductive activities of aquatic life.

Of the dissolved ions, Ca$^+$, Na$^+$, Mg$^{2+}$, and K$^+$ and Cl$^-$ are usually primarily derived from the ground, and SO$_4^{2-}$, NO$_3^-$, and NH$_4^+$ are usually primarily derived from atmospheric gasses, but the source of inputs is spatially variable (Allan and Castillo, pg. 60, 2008). Dissolved inorganic nitrogen and phosphorous (NO$_3^-$, NH$_4^+$, and PO$_4^{3-}$) cycle rapidly through inorganic to organic phases, and are the primary nutrients that limit plant and microbial production (phosphate is usually the limiting nutrient). Nitrate levels of most surface waters throughout the world are less than 5 mg L$^{-1}$, and 0.4 to 1.4 mg L$^{-1}$ in continental rain (Allan and Castillo, pg. 58, 2008; Livingstone, 1963). Nitrogen and phosphorous concentrations are increasing in many surface waters of the world, causing
Cattle feces contain both nitrogen and phosphorous, and are dissolved and decomposed to form $\text{NH}_4^+$, $\text{NO}_3^-$, and $\text{PO}_4^{3-}$ in water. Nitrate and phosphate are most stable in the water column, and are therefore analyses typically measure these ions.

The measurement of DO provides the amount of oxygen available for use within the water column. DO is important because oxygen has a low solubility and low diffusion rate in water, especially stagnant waters. Rapid utilization of $\text{O}_2$ can result in anaerobic conditions. Oxygen is produced by aquatic plants (via respiration during the day) and is used by aquatic animals. The concentration of saturated dissolved oxygen in pure freshwater at sea level is 9.8 mg/L at 15 °C, 7.5 at 30 °C, and 14.2 at 0 °C (Allan and Castillo, pg. 58, 2008). DO concentration is affected by many things, including temperature, turbulence, aquatic plants, altitude, nutrient loading, dissolved and suspended solids.

ORP is measured to determine the oxidizing or reducing potential of the water. Aerated surface waters usually have oxidizing conditions (500 to 800 mV at pH 7), and anaerobic systems such as swamps and saturated substrates usually display reducing conditions, which are indicated by redox potentials, at pH 7, below 200 mV (DeLaune and Reddy, 2005).

pH is the measurement of hydrogen ion activity, which determines the acidity of the water. Too acidic or basic waters become toxic for aquatic life, and changes in pH can change important aspects of water chemistry, such as the level of nitrogen present as ammonia and solubility of metals and other compounds.

Conductivity is a measure of how well the water can pass an electric current, and increases with increasing inorganic dissolved solids. Many parameters can be estimated from conductivity without directly measuring them, including total dissolved solids and salinity.

Turbidity measures the amount of un-dissolved suspended sediments in the water column, such as soil particles, plant particles and plankton. High turbidity blocks out the sunlight and reduces opportunities for photosynthesis of
submerged plants. Both conductivity and turbidity increase with evaporation rates higher than input rates, such as precipitation.

2.4. **Existing Data on Oregon’s High Desert Vernal Pools**

Very little research has been done on Oregon’s high desert vernal pools. The semi-arid climate of the area has long, severe winters and short, dry and hot summers. Specific temperature and precipitation are spatially and temporally variable, in part due to the high intensity, low range storms that occur in the high desert. Great fluctuations between drought and high precipitation often occur (Dlugolecki, 2010). In the Hart Mountain Antelope Refuge, January temperatures range from -16 to 9.7 °C on average, and July temperatures range from 9.2 to 28.3 °C on average (Western Regional Climate Center, 2013). Precipitation is usually 150 to 300 mm per year, with most of that falling as snow from November through March, then as rain from March through May (Western Regional Climate Center, 2013).

Most pools in the region visited were dry by late spring, especially unaltered pools that do not have an excavated pit in them, or in the natural portions of basin that did have a dugout. However, the largest natural pools visited were witnessed to contain ponded water in September in 2011 (a particularly wet year; the largest ones may not have dried at all), and August in 2012.

Clausnitzer (2000) and Clausnitzer and Huddleston (2002) conducted a three year study of a single vernal pool in Oregon’s high desert, where they detected dissolved CaCO₃, soluble salts and exchangeable cations. The soils had relatively low iron due to parent materials, relatively low organic matter due to low biomass production, low redoximorphic features due to low carbon levels and small amounts of iron and manganese, and high pH due to evaporative accumulation of salts.

Water quality samples were taken in the region by the BLM Prineville District, for water rights allocation purposes. Parameters measured were limited
to conductivity, temperature, and pH, and were regarded as “passing” when applied to the Oregon Department of Environmental Quality (ODEQ) section 303(d) for impaired waterways as a reference for standards, because no standards exist specifically for vernal pools (Michelle McSwain and Jenny Mofitt, Prineville BLM, personal communication). Macro invertebrate sampling was also done by BLM at multiple altered and un-altered vernal pools; the highest macroinvertebrate diversity was recorded at an un-altered pool.

Existing water chemistry data on the regional watersources is otherwise limited to large waterbodies in the area. Phillips and Denburgh (1971), gathered data on lakes in south-central Oregon for water chemistry parameters, primarily focused on Lake Abert, Summer Lake and Goose Lake. Additionally, Johnson et al. (1985) provided data from one time point at nearby Lake Abert (Table 1). These data indicate a wide variability of conditions found, suggesting water quality of water sources in the region are difficult to classify.

Table 1. Range of Water Chemistry Values Recorded in Nearby Lakes

<table>
<thead>
<tr>
<th></th>
<th>Lake Abert, from Johnson et al. 1985</th>
<th>Lakes in Area, from Phillips and Denburgh (1971)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Sulfate, mg L⁻¹</td>
<td>NA</td>
<td>0.2</td>
</tr>
<tr>
<td>Chloride, mg L⁻¹</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Fluoride, mg L⁻¹</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Bromide, mg L⁻¹</td>
<td>NA</td>
<td>1</td>
</tr>
<tr>
<td>Nitrate, mg L⁻¹</td>
<td>NA</td>
<td>0.6</td>
</tr>
<tr>
<td>Phosphate, mg L⁻¹</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Specific Conductance, mS cm⁻¹</td>
<td>2</td>
<td>0.056</td>
</tr>
<tr>
<td>pH</td>
<td>10.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Dissolved Oxygen, mg L⁻¹</td>
<td>9.5</td>
<td>NA</td>
</tr>
</tbody>
</table>
This study was conducted to develop baseline water quality data on a broad spatial range of vernal pools with various levels of alteration in Oregon’s high desert, and to see if there is a clear difference with respect to water quality.

2.5. Materials and Methods

Study Area and Site Descriptions

The study area includes vernal pool sites from Deschutes, Lake and Harney counties (primarily in Lake), spanning across Central to Eastern Oregon, and South to near the Nevada border (Figure 10). Twenty seven vernal pool basins containing water, and approximately 83 more dry basins, were visited during July through September, 2011 and February through September, 2012 to aid in the development of baseline information\(^3\). Of the basins sampled, six natural and nine altered were re-visited during a different water stage.

Figure 10. Location of Study Area and Vernal Pools Sampled

Of the pools sampled for water quality parameters, eight were natural (no obvious alterations) and 19 had altered topography (Figure 11 and Figure 12).

\(^3\) Contact the author for general notes data on all visited sites, including site coordinates, ponding presence/absence data and dates, water quality raw data, or general site descriptions.
Twenty of the pools were open to cattle, and seven were in the Hart Mountain National Antelope Refuge where cows are excluded. In addition to the pools, six metal guzzlers and 11 excavated dugouts in random locations (not inside vernal pool basins) were repeatedly visited across the study area for water quality parameter comparisons of water source alternatives to the vernal pools (Figure 13 and Figure 14).
Figure 11. Natural Basins. Photographs by author.
Figure 12. Altered Basins. Photographs by author.
Figure 13. Dugouts Outside of Basins. Photographs by author.
Figure 14. Guzzler. Photograph by author.

Field Methods

A YSI 6920-V2 Multiparameter water quality sonde, with full temperature compensation readings, was used for field sample collection. The sonde measures water quality parameters temperature, conductivity, pH, ORP, turbidity and DO. All critical activities were documented in a field notebook, such as the times of sonde sample points. General observations of the pools were also documented, such as evidence of biological use, ephemeral tributaries, change in conditions, etc.

Field sampling was done in a way to minimize sampling error. Sampling was always performed when there was no precipitation occurring. Agitation of the pools was kept to a minimum while samples were collected. An extension

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4 Refer to Appendix 2 – Water Quality QA/QC Protocols for in-depth details on QA/QC procedures, equipment operation, calibration and maintenance, the validated acid washing procedure performed, and additional field methodology.
rod and accompanying stand were created in order to sample away from the immediate bank of the pools without wading into them (Figure 15).

![Sampling extension rod and stand used for sampling to minimize water disturbance](image)

**Figure 15. Sampling extension rod and stand used for sampling to minimize water disturbance**

While this worked well for the dugouts, it was usually impossible to sample the natural pools without wading into them, as the outer perimeters of the pools were too shallow and the change in slope was too small to reach a sampling depth adequate to submerge the sonde bulkhead without wading in. In these situations I had to wade in, but would stand still until particles settled, and the sampling rod was still used to sample away from the disturbed area (Figure 16).
Figure 16. Use of sampling extension rod at a dugout (top) versus natural pool (bottom)

Grab samples were taken into HDPE bottles for Ion Chromatography (IC) analysis, also using the extension rod. All materials that came in contact with the samples were acid washed according to a standardized and validated acid washing procedure prior to contact. The bottles were rinsed with environmental water in the field prior to sample collection. Samples were collected from approximately the center of the water column.

Grab samples were filtered down to 0.4 µm and frozen to await IC analysis. The OSU Institute for Water and Watersheds Collaboratory IC was
used for common anion analysis to evaluate water samples for nitrates, and the analysis also automatically included fluoride, chloride, bromide, phosphate and sulfate.

Due to the highly remote locations of the sites, vernal pool sampling could not occur at regular times of day to control for natural daily fluctuations that occur in temperature, pH, dissolved oxygen and redoxemorphic parameters due to daily temperature and photosynthesis patterns.

Data Analysis

The data from Oregon’s high desert water sources were organized and analyzed for patterns in various ways in an attempt to determine controlling factors of water quality. First, the sites were categorized into five groups based on their most distinct physical characteristics differences (Table 2), dugouts that exist outside of a natural basin, dugouts that exist inside of a natural basin, altered basins, natural basins, and man-made guzzlers. The overall averages of each site type were graphed to compare for differences. The data from dugouts inside a basin where water only existed in the basin during the sample date was included in the dugouts inside basin average, and not included in the altered average. When a dugout was overflowing into the natural portion of the basin, and the sample was taken there, it was included in the altered category.
Table 2. Data Categorization by Physical Characteristics

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Number of Sites</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guzzler</td>
<td>Man-made water feature, usually made from metal; pump or gravity fed.</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>Natural</td>
<td>Natural basin with no evidence of anthropogenic modification.</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Altered</td>
<td>Most closely resembles a natural basin, but evidence of anthropogenic activity, such as one bermed side, or sampling in the natural portion of a full basin where the water is connected to water that exists in a dugout in the basin.</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Dugout Inside Basin</td>
<td>Distinct dugout located inside of a natural basin; water only located in dugout during sampling.</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Dugout Outside Basin</td>
<td>Highly artificial: distinct dugout in the ground that is not in a natural basin.</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>46</td>
<td>100</td>
</tr>
</tbody>
</table>

Next, the data were reclassified again into three different categories: pools that exist where cows have access to them, pools that exist within the Hart Mountain National Antelope Refuge where cows have been excluded since 1990 for a 15 year rest period, and all guzzlers.

Finally, the data were organized to evaluate temporal change of the water systems. The same classification scheme used to compare overall averages was used for this (Table 2), except altered pools and dugouts in basins were combined into one category (with the name altered), as one vernal pool basin with a dugout in it could switch from an altered category to a dugout category later in the season, as the water dries from the natural portion of the basin and only exist in the dugout located in the basin. How these basins change when water retreats from the natural portion of a basin to just the dugout can be seen. The other categories remained the same. The temporal variation graphs only include data from sites that were visited more than once, so the total number of
sites and number of samples are less. Sampling was performed on the following dates:

Statistics

SPSS statistics software was used to run independent samples T-tests to compare different site type groupings for differences. Two sites are compared at a time with this analysis. Site types compared were:

- Natural vs. Altered pools
- Dugouts Inside Basins vs. Natural pools
- Dugouts Inside Basins vs. Altered pools
- Dugouts Outside Basins vs. Natural pools
- Dugouts Outside Basins vs. Altered pools
- All altered pools grouped together (DIB and altered) vs. Natural
- All vernal pools grouped together vs. Guzzlers
- All vernal pools grouped together vs. Dugouts Outside of Basins
- Cow exclusion pools vs. cow inclusion pools

The spatial autocorrelation tool in ArcGIS was used to evaluate the spatial influence on each parameter value for all ground-based sites (i.e., all sites except guzzlers). Only one sample per site was included to eliminate repeated sample bias. This tool provides an indication of whether a spatial variable is controlling the parameter values seen. The tool parameters were set so the spatial relationships were evaluated with inverse distance and row standardization.

2.6. Results

The overall range of values recorded at the various site types were highly variable for all of the parameters (Figure 17). The results from categorizing the
sites by their physical characteristics show subtle differences between site types in some of the parameters, and dramatic differences in other parameters (Figure 18).\textsuperscript{5} Categorizing the sites based on cow exclusion, cow inclusion or guzzlers showed little differences (Figure 19). Temporal graphs of each parameter show one representative site from each category (Figure 20 through Figure 22).\textsuperscript{6}

Data from two sites were omitted from grouping and averaging results (but not from overall ranges or temporal variation) due to unique observations at those sites that may have influenced the water quality recorded. One of these sites was omitted because an ephemeral spring input was observed during the first visit of observation. The second site was omitted because it was a dugout inside of a basin, the dugout portion was fenced in with a gate, and it was suspected that cattle are fenced in occasionally. Outlier parameter results and unusual temporal trends at these sites supported these theories.

\textsuperscript{5} Refer to Table 8 through Table 15 in Appendix 4 – Water Quality Data Tables for data summaries of all site types.
\textsuperscript{6} Refer to Figure 44 through Figure 55 in Appendix 3 – Temporal Variability of Water Quality Parameters for temporal graphs of every site that was sampled more than once.
Figure 17. Results of Total Range of Values for Physical Classification – 1 of 2
Figure 17. Results of Total Range of Values for Physical Classification – 2 of 2
Figure 18. Results of Average Values of Physical Classification – 1 of 2
Average for measured parameters, including error ranges, for the five physical types.
Figure 18. Results of Average Values of Physical Classification – 2 of 2
Average for measured parameters, including error ranges, for the five physical types.
Figure 19. Results of Average Values of Cow Access and Guzzlers – 1 of 2
Average for measured parameters, including error ranges, for the five physical types.
Figure 19. Results of Average Values of Cow Access and Guzzlers – 2 of 2
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Figure 20. Temporal Change of Temperature, Conductivity, pH, and ORP at Representative Sites of Each Site Type.
Figure 21. Temporal Change of Turbidity, DO, Nitrate and Phosphate at Representative Sites of Each Site Type.
Figure 22. Temporal Change of Chloride, Bromide, Sulfate and Fluoride at Representative Sites of Each Site Type.
**Temperature**

The average temperatures of physical site types ranged from about 17 to 21 °C, and the overall range of values were 4.4 °C (natural pool) to 29.2 °C (altered pool). The average temperatures of the different site types were not statistically different from each other, except that temperature was lower in guzzlers than in all vernal pool types combined (p=0.031), and the temperature of pools where cows are excluded was significantly higher than the temperature of sites that are open to cows (p = 0.025). As expected, when looking at temporal change, temperature mostly increased throughout the seasons.

**Specific Conductivity**

The average specific conductivity values of physical site types ranged from about 0.3 to 0.7 mS/cm, and the overall range of values were 0.06 mS/cm (altered pool) to 4.7 mS/cm (natural pool). Specific conductivity was not statistically different in any of the ground sites compared to each other, or in cow inclusion vs. exclusion sites. It was statistically higher in all vernal pool types grouped together than in guzzlers (p=0.017). Temporally conductivity consistently increased throughout the season, except for in guzzlers which remained low and more or less constant.

**pH**

The total range of values were pH 6.9 (natural pool) to pH 10.2 (dugout outside of a basin). For grouping and averaging, the hydrogen ion concentration [H+] was calculated and used rather than pH. [H+] was not statistically different in any of the ground sites compared to each other, or in cow inclusion vs. exclusion sites. It was statistically higher in all vernal pool types grouped together than in guzzlers (p=0.040). A higher hydrogen ion concentration in the vernal pools means a lower pH.
ORP

ORP averages of physical site types ranged from about 80 to 115 mV, and the overall range of values were -224 mV (dugout outside of a basin) to 222 mV (dugout inside of a basin). ORP was not statistically different between any of the site types. The temporal results of ORP showed an almost consistent decline throughout the seasons, although small increases were occasionally seen. Two notable outlier data points of ORP values occurred when the sites were almost completely dry, and were described as being “sludgy”. These values existed in a dugout outside of a basin and a dugout inside of a basin, and indicated extremely anaerobic conditions (-103 and -224 mV).

Turbidity

Turbidity averages of physical site types ranged from about zero to 900 NTU, and the overall range of values were 0 NTU (guzzler) to 1,340 NTU (altered pool). Guzzlers were close to zero at almost every reading, and were dramatically lower than all other types (p=0.000). For the pool types, turbidity was highest in dugouts inside of basins, followed by dugouts outside of basins, altered then lowest in natural pools. Turbidity was statistically higher in dugouts inside of basins than in natural pools (p=0.001), higher in dugouts inside of basins than in altered pools (p=0.052), and higher in dugouts outside of basins than natural pools (p=0.027). Turbidity was not statistically different between dugouts inside of basins and dugouts outside of basins, between dugouts outside basins and altered pools, or between natural and altered pools. When grouping both types of dugout vernal pools together (dugouts inside of basins and altered pools), turbidity was higher than in natural pools (p=0.011). Turbidity was not different between pools open to cows than in the cow exclusion area. Temporal change of turbidity of the pools was variable. Most of the time it increased as the seasons progressed, as would be expected as the pools dry and suspended solids becomes more concentrated. However, in 2012 turbidity decreased in the natural pools, and several of the altered pools that most closely resembled natural pools.
Dissolved Oxygen

Dissolved oxygen averages of physical site types ranged from about 7 to 12 mg L\(^{-1}\), and the overall range of values were 0.29 mg L\(^{-1}\) (dugout inside of a basin) to 33.6 mg L\(^{-1}\) (dugout outside of a basin). The only statistical difference shown was DO was higher in dugouts outside of basins than in all vernal pool site types combined (p=0.030).

Nitrate

Nitrate averages of physical site types ranged from about 0.1 to 1.0 mg L\(^{-1}\), and the overall range of values were 0 mg L\(^{-1}\) (all site types had at least one sample of 0 mg L\(^{-1}\)) to 18.3 mg L\(^{-1}\) (dugout inside of a basin). There were no statistical differences in nitrate between any site types except it was higher in guzzlers than in all vernal pool types combined (p=0.031). Temporal change of nitrate in the pools was variable. Most of the time it increased as the seasons progressed, as would be expected as the pools dry and ions become more concentrated. However, in 2012 nitrate decreased in the natural pools, and in several of the altered pools that most closely resembled natural pools. In the pools where nitrate decreased over time, turbidity decreased in the same pools over the same period of time.

Chloride

Chloride averages of physical site types ranged from about 5 to 25 mg L\(^{-1}\), and the overall range of values were 0 mg L\(^{-1}\) (natural) to 274 mg L\(^{-1}\) (dugout inside of a basin). Chloride was not statistically different in any of the site types. Chloride increased throughout the seasons in all site types except guzzlers, and in one dugout outside of a basin that was initially well water fed.

Bromide and Fluoride

Bromide averages of physical site types ranged from about 0.05 to 0.2 mg L\(^{-1}\), and the overall range of values were 0 mg L\(^{-1}\) (all site types had at least one sample of 0 mg L\(^{-1}\)) to 1.1 mg L\(^{-1}\) (dugout inside of a basin). Fluoride
averages of physical site types ranged from about 0.2 to 0.7 mg L\(^{-1}\), and the overall range of values were 0.02 mg L\(^{-1}\) (natural pool) to 3.3 mg L\(^{-1}\) (dugout inside of a basin). Bromide and fluoride demonstrated very similar concentration patterns across site categories. There were no statistical differences in bromide or fluoride between any of the site types. Bromide and fluoride both consistently increased throughout the seasons in the sites, except for guzzlers which were not seasonally dependent, and the two dugouts outside of basins that had outside influences (ephemeral spring input and initial well water input), which decreased slightly with time.

**Phosphate**

Phosphate averages of physical site types ranged from about 0.5 to 4.2 mg L\(^{-1}\), and the overall range of values were 0 mg L\(^{-1}\) (all site types except natural pools had at least one sample of 0 mg L\(^{-1}\); the natural minimum was 0.02 mg L\(^{-1}\)) to 21.7 mg L\(^{-1}\) (dugout outside of a basin). There were no statistical differences in nitrate between any site types except it was lower in guzzlers than in all vernal pool types combined (p=0.007). However, phosphate was the only parameter that showed statistical spatial dependence (p=0.000). Phosphate almost consistently increased as seasons progressed, except for one of the nine altered pools where it increased then decreased, guzzlers, and in the two dugouts outside of basins that had outside influences (ephemeral spring input and initial well water input), which decreased.

**Sulfate**

Sulfate averages of physical site types ranged from about 2 to 18 mg L\(^{-1}\), and the overall range of values were 0.01 mg L\(^{-1}\) (natural) to 113 mg L\(^{-1}\) (dugout outside of a basin). There were no statistical differences in sulfate between any site types except it was higher in dugouts outside of basins than in all vernal pool types combined (p=0.048). Sulfate consistently increased in all non-guzzler sites except for the two dugouts outside of basins that had outside influences (ephemeral spring input and initial well water input).
2.7. **Discussion and Conclusions**

Plotting individual pools over time showed parameters in a given location do change up or down, although they do not always trend consistently for each parameter (e.g., the dissolved oxygen increased throughout the season for some pools and decreased for others over the same time period). Unsurprisingly, guzzlers demonstrated the least correlation of parameter values over time. Variation in guzzler parameters is probably at least partially attributable to whether or not well water was actively flowing into the guzzlers or not during sampling. Although guzzlers are also fed by precipitation, the primary input of water comes from groundwater, which likely contributes to the variable chemical composition seen in them.

Parameters that tended to increase in non-guzzler sites throughout the season were temperature, turbidity, conductivity, and the anions. However, nitrate decreased over time only in the natural pools, and slightly decreased in several of the altered pools that most resemble natural pools. Turbidity also decreased with time in the same natural and altered pools over the same period of time, while increasing in others. ORP tended to decrease throughout the seasons, showing increasingly anaerobic conditions as the pools dry and warm up. DO also tended to decrease throughout the seasons, although less consistently than expected.

One possible reason for the decline in turbidity over time in the natural pools and an increase over time in the dugouts is that exposing the water to the deeper soil horizons has altered the chemistry and therefore the chemical processes that occur. Clausnitzer and Huddleston (2002) conducted a soil analysis on a vernal pool within the study area, which showed that the deeper horizons have very different chemical compositions than shallow horizons, including an astoundingly higher sodium level in deeper horizons (Figure 23). The concentration of sodium increased from 0 mg L$^{-1}$ in the shallow horizons to 508 mg L$^{-1}$ in the 2Bss2 horizon.
The higher sodium is interesting because sodium has a large ionic radius, and therefore has the potential to organize itself in between negatively charged suspended clay particles, but keep the clay particles separate and suspended. In the pools that have been dugout into these lower soil horizons, it is possible a higher sodium concentration is keeping the clay suspended, and the turbidity continues to concentrate as the water declines. Without the abundance of large cations in the natural pools, the clay could be aggregating and settling out of the water column as the water level declines. Further research would need to be conducted to test this theory, but it might also explain why the only statistical differences seen in site type averages was a higher turbidity in sites with dugouts than in unaltered basins. Dugouts inside of basins and dugouts outside of basins have higher turbidity than altered and natural pools, demonstrating higher concentration of suspended sediments in the excavated dugouts.

The extreme increase in concentration of nitrate with soil depth also could explain why nitrate levels increased over time in the dugouts, but it doesn’t explain why it decreased in the natural pools. This phenomena might be due to higher denitrification capability in the natural pools than in altered or artificial pools. Another theory is that either nitrate or turbidity is controlling the other one,
such as higher nitrate assimilation occurs with decreasing turbidity due to the increase of light allowed into the water column, and therefore a correlating decrease in nitrogen. The data suggest altering vernal pool basins reduces these processing capabilities of vernal pools.

As would be expected, ions tend to become more concentrated as the pools dry. Interestingly, the overall concentration of ions in natural pools is lower than in dugouts inside basins. This is surprising because the natural pools tended to be shallower during sampling than the dugouts inside basins, and dried out earlier. If the two types were otherwise equal (e.g., the water levels were the same in both), natural pools would likely contain even a lower concentration ratio of particulates such as nitrate and chloride than dugouts inside basins. Comparing the data taken at sites with extremely low water levels with those taken at higher levels supports this notion. Extreme values of chloride and nitrate showed up in very shallow dugouts, but not in very shallow natural basins.

Temporal graphs of DO did not show consistent increases or decreases throughout the seasons, although decreases were more common and the magnitudes of decreases were higher than for increases. The exception to this is one dugout outside of a basin site that was suspected to have an ephemeral spring input during the very first visit, which showed dramatically low DO early in the season, and sharp increases throughout each season. This supports the theory that an ephemeral spring exists early in the season, as groundwater has much less oxygen than surface water.

Since the cow exclusion pools were only sampled in the summer, higher pH levels would be expected since pH is typically increased in the summer when more plankton is present (e.g., Elbert and Fox, 2005; Goldyn, 2008). The pH average of the cow exclusion area pools would likely have been even lower if it included readings from earlier in the season, enhancing the difference. The temporal graphs of pH show increasing values in the hot portion of the 2012 summer months, but otherwise seems to have been non-dependent on the time of year before about July 2012. Due to daily fluctuations in pH not being controlled for, these results should be considered approximate.
Dissolved oxygen and pH values did not tend to demonstrate correlations with seasonality, but this may be because they both vary diurnally, and this was not controlled for during sampling. The range of values measured still provides useful baseline information on magnitudes expected to be encountered in vernal pools in the study area. pH values showed the systems tend to be on the basic side for supporting life, so small variations in pH in the area might greatly change species distributions. The initial data show lower pH levels in vernal pools than in guzzlers. The pH in natural basins ranged from 6.9 to 8.9, while the other sites had ranges from over pH 7 to 10, except for dugouts inside basins which had an upper limit of pH 9.1. Dissolved oxygen levels exceeded the healthy upper limit of 110% saturation in at least one site in every category except for natural pools, which had 110% as the highest saturation. One dugout outside of a basin had a saturation of 497%. On the other extreme, one dugout inside of a basin had the lowest saturation of just 3.2%, while the natural pool minimum was 16.8%. Based on the ranges of values recorded in the various site types, natural and altered pools seem to have pH and DO values more equipped to sustain life.

Nitrate was not significantly different in any of the ground-based sites (i.e., non-guzzlers). A close look at the data show a relatively large spike in nitrate between time points at one of the sites (from 0.3 to 4.6 mg L\(^{-1}\)), when the water became extremely low. This gives an idea of how the concentration of nitrate can increase when the water becomes very low in a dugout. Similarly low water levels in natural basins did not produce nitrate results to this extreme. Nitrate was not correlated with time of year for guzzlers.

One of the outlier sites that was removed from the average analyses was a dugout inside of a basin that was sampled twice. The pool had extremely high nitrate values compared to the rest of the data (7.9 and 18.3 mg L\(^{-1}\)). The site was the only one visited that was about 95% fenced off in a small area inside the basin, around the dugout, and had a gate that could close it off completely. The extreme nitrate values may be due to different management of the pool, such as cattle being fenced in a very small area around the pool for periods of time.
Some samples were re-run on the IC after being stored for months with a new dilution in an attempt to obtain better peak resolution on the chromatography. Re-analysis demonstrated a sharp increase in nitrate levels in some of the samples while in storage, which is an indication that high levels of un-ionized ammonia (NH$_3$-N) were initially present in the sample and were converting to nitrate while in storage. Future studies could incorporate an analysis of rates of nitrate increases while in storage, or could directly measure ammonia to get a better sense of the levels and form that exist in these systems.

There was also an extreme spike in chloride between time points at one of the sites (from 17 to 274 mg L$^{-1}$), when the water became extremely low. Similarly low water levels in natural basins did not produce extreme chloride results either. Chloride increased throughout the seasons in all site types except guzzlers, and in one dugout outside of a basin that was initially well water fed.

Sulfate consistently increased in all non-guzzler sites except for the two dugouts outside of basins that had outside influences (ephemeral spring input and initial well water input), both of which could explain the initial decrease in sulfate.

The water quality of the guzzlers is certainly different than the pools. The most distinct difference was the extremely low turbidity compared to the extremely high turbid pools, most likely due to the high clay composition of the soil. Guzzlers also clearly had higher conductivity, pH, nitrate, sulfate levels, and lower temperature and phosphate levels than the ground sources. Things that may have affected this include lack of contact with the substrate, or chemical input from the ground water source that they originate from.

Dugouts outside of basins had the most variable and unpredictable results after guzzlers. This is likely due, in part, to the fact that the definition of a dugout outside of a basin was otherwise broad, and included holes in the ground of variable appearance. Additionally, it was thought that a spring was witnessed at one of the regularly visited pools during the first visit, although it was never seen again and the pool did dry up. Temporal fluctuations of parameters in this dugout
were often opposite of other dugouts. Also, another dugout outside of a basin had a well pipe running into it that was occasionally flowing.

Altered pools and natural pools displayed the most similar overall water quality parameters to each other, which isn’t surprising given that they are the most physically similar. The water quality of the altered pools most resembled natural pools when the dugout was “overflowing” into the natural basin, and the parameters changed when they dried to only exist in the dugout.

Cow inclusion sites were areas that were open to cows. However, although cows and evidence of cows were often witnessed at the sites, verification that all sites actually are used by cows was not performed, nor was analysis of the intensity of cow use at individual sites. The cow exclusion vs. inclusion results in this study should therefore be considered a preliminary glance at potential impacts of cows on the vernal pools in the region rather than as a definitive cow exclusion study. Higher temperatures in the cow exclusion zone can likely be explained by the fact that the cow exclusion area was only visited during summer months, and the data for areas open to cows and guzzlers include late winter, spring and summer time points. The discrepancy could affect other results for things that naturally vary with temperature, such as ORP and dissolved oxygen. However, since the pools in the cow exclusion zone tended to hold water later into the year, water quantity and parameters quantity might affect (e.g., turbidity) were considered equal. Instances where they dropped down throughout the season are most likely due to earlier in the day sampling times.

Differences other than temperature could not be shown between the water quality of vernal pools open to cows and the water quality of vernal pools closed to cows. Although it may be the case that differences actually do not exist between the two categories in the region, additional research is needed to draw any conclusions about the data, particularly since previous studies have shown cattle to affect vernal pool ecosystems and water quality (e.g., Croel and Kneitel, 2011). Spatial distribution considerations must also be taken into account, as the sites of cow exclusion are spatially clumped together in the Hart Mountain National Antelope Refuge; an area that may have unique geological composition.
Spatial autocorrelation analyses in this study do not show spatial dependence in the region for any of the parameters other than phosphate, which was not of consequence since phosphate was not shown to be different between cow inclusion and exclusion sites. The spatial autocorrelation results of phosphate mean that phosphate levels in the non-guzzler water sources are not randomly distributed across the study area. Therefore, a spatial component such as wide-range soil distribution is likely a major controlling factor in phosphate levels in the water sources.

Since the official classification and mapping of vernal pools in the area has yet to be done, it is unclear if all of the pools sampled ought to be classified as vernal pools, such as the ephemeral systems in the Warner Valley Wetlands. It is clear that excavated dugouts that exist in areas that do not have natural basins should not be considered vernal pools and are included for comparison purposes only. Further analyses of vegetation and animal use of Oregon’s high desert vernal pools would aid in the accurate classification and appropriate management for these crucial systems.

Future research should be conducted to further characterize Oregon’s high desert vernal pools and to answer some of the additional questions that arose from this study. An intensive short term study during the ponded season could clarify whether or not more differences exist between altered and unaltered pools. A complete chemical analysis including metals and chlorophyll would further develop baseline data in the systems and aid in the understanding of controlling processes occurring in the systems, such as the reason turbidity is higher in the dugouts.

Although some patterns can be seen by categorizing the water source types sampled in the study area, the data clearly show high variability in water quality parameters within each site type, with extreme ranges with respect to the medians. Data available on large lakes in the region seem to lack a clear pattern as well (Table 1). These variations seem to be determined by temporal change within and between years, variable management, and possible geophysical
variability. This data suggests that little can be assumed about existing water quality conditions of Oregon’s high desert vernal pools, and that they are unique.
2.8. References


QUANTIFICATION OF OREGON’S HIGH DESERT VERNAL POOLS’ SURFACE AREAS USING REMOTE SENSING AND GIS ANALYSIS

Sara A. Wyland
3. QUANTIFICATION OF OREGON’S HIGH DESERT VERNAL POOLS’ SURFACE AREAS USING REMOTE SENSING AND GIS ANALYSIS

3.1. Abstract

Vernal pools vary greatly in their distribution, hydrology and hydrologic connectivity (seasonally and spatially). Since hydrology is the driving force for ecologically important functions of vernal pools, it is important to clarify the seasonal status of vernal pools regionally. Timing of vernal pool ponding in Oregon's high desert has not been adequately documented. Vernal pool water quantity information is difficult and time consuming to monitor in situ. Remotely sensed images provide an opportunity to efficiently derive surface area water quantity information of the pools. This study was conducted to define a method for deriving broad scale surface area water quantity information of Oregon’s high desert vernal pools. SPOT multispectral images were determined to be most appropriate for extracting water surface areas based on a satellite image suitability assessment. ArcGIS tools and Python script were used to process images, performing a supervised classification of SPOT raster images, conversion to polygon shapefiles, and calculations of water surface area polygons. The method is limited temporally by the availability of suitable images. The method does not differentiate vernal pools from other surface water sources, but this does not remove the value for analyzing vernal pool status. The method was found to be capable of efficiently deriving vernal pool surface areas across a broad range of high desert from the SPOT images.

Abbreviations: NWI: National Wetlands Inventory; SWIR: Short Wave Infrared; DEM: Digital Elevation Model.

3.2. Introduction

Vernal pools are surface water wetlands that undergo an annual cycle of filling, ponding, drying, and desiccation. The duration of ponding typically lasts for a few weeks to a few months, depending on the water holding capacity of the
soil, position in the landscape, precipitation and evapotranspiration rates (between and within years) and depth of the depression (Bauder, 2005; Robins and Vollmar, 2002). The unique hydrological regime leads to ecologically important functions, such as serving as breeding and rearing grounds for many species, and they tend to become isolated micro-regions of high biodiversity. The reliable returning presence of water to a vernal pool bed is the defining character that allows specialized and unique biota to develop, and discourages upland plants from encroaching (Williamson et al. 2005; Zedler, 2003). The wetland plant species that inhabit the vernal pools will vary also with duration of ponding. For example, facultative-wet or obligate plants will be more correlated with vernal pools with longer hydroperiods than shorter (Adamus, 2006). Bliss and Zedler (1998) showed that vernal pool specific species tend to not germinate under un-favorable conditions (temperature and precipitation timing), and therefore may not be resilient to climate change, giving generalizing species a higher competition factor.

Hydrologic connectivity can be an important driver of vernal pool water chemistry, biodiversity, vegetation structure and net primary productivity (Cook and Hauer, 2007). Loss of vernal pool connectivity can also lead to amphibian declines due to their pool and overland dispersal behaviors, and a decline in their connections to other populations (Compton et al. 2006; Semlitsch and Bodie, 1998). Therefore, their ability to withstand stochastic fluctuations is decreased, demonstrating the importance of looking at vernal pools on multiple scales (Compton et al. 2006; Oscarson and Calhoun, 2007).

Lengthening the duration of water ponding by partial excavation of vernal pool basin to and to act as a stock pond is common (Clausnitzer and Huddleston, 2002). Increased ponding duration could lead to increased range of large herbivores (livestock and native) later into the year, into areas they would typically not go due to lack of water (Clausnitzer and Huddleston, 2002; Landsberg et al. 1997). The establishment of aquatic plants could also occur, and encourage proliferation of predaceous aquatic insects, and reduce native and unique species (Clausnitzer, 2000; Clausnitzer and Huddleston, 2002;
Graham, 1997; Roth and Jackson, 1987; Weir, 1971). Vernal pool ponding duration is likely sensitive to climate variability due to the ephemeral nature. Although the bankfull surface water boundaries in Oregon’s high desert have been extensively mapped on high resolution road atlases and the National Wetlands Inventory (NWI), details of temporal variability of surface areas is unknown. Information about water quantity allows us to understand water availability for wildlife and livestock, temporal variability of water sources, and how water quantity and water quality parameters are correlated. Water quality data was collected on select pools in Oregon’s high desert from July through September of 2011, and February through September of 2012. It was not feasible to monitor the water quantity of the pools during field visits, as it changes greatly over time and the process of measuring water quantity is extremely time consuming. Previous studies have shown that remotely sensed images can be used to aid in mapping vernal pool water quantities (e.g., Hass et al., 2009; Kashaigili et al., 2006; Lathrop et al., 2005), although published work of this type is limited and does not include the Northern Great Basin. Determination of water surface areas can be used as a general measure of the overall change of vernal pool water availability and can aide in management decisions and field sampling scheduling. The intent of this study was to outline a method for quantifying Oregon’s high desert vernal pool water surface areas at the times suitable satellite images were taken, in order to clarify the seasonal and long term variation of the pools. The method was used during the 2012 field season to check for water presence prior to field visits saving a significant amount of time and gas by not travelling to dry basins.

3.3. Materials and Methods

Study Area

The study area spans across Central to Eastern Oregon, and south to the Nevada border. Hundreds of pools within the study area were monitored as part
of this project. The extent of the study area, and the location of the specific representative pools chosen for method development are presented (Figure 24).

Figure 24. Study Area and Locations of Representative Pools Used in this Analysis

Discussion of Data:

A satellite image suitability assessment was performed on vernal pools within the study area, to determine which satellite images had spatial and temporal resolutions great enough to adequately characterize the vernal pools. Many study area vernal pools were viewed in each type of satellite, and three of the larger ones are included for visual comparison of spatial and spectral resolution (Figure 25).
Many satellite data sources were considered, but the full analysis was performed on a subset determined by the highest spatial, temporal and spectral resolution data (Table 3). In addition to those listed, Landsat data was also considered due to its free accessibility, but since many vernal pools are small, the 30 m spatial resolution wouldn’t adequately capture many of the smaller pools (Lathrop et al., 2005).
Table 3. Overview of Satellite Image Specifications
Source: Miller, 2007

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Image Descriptions</th>
<th>Spatial Resolution</th>
<th>Spectral Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER</td>
<td>Panchromatic; VNIR</td>
<td>15 m</td>
<td>0.52 – 0.86 µm</td>
</tr>
<tr>
<td>SPOT 4</td>
<td>Panchromatic</td>
<td>10 m</td>
<td>0.61 – 0.68 µm</td>
</tr>
<tr>
<td>SPOT 4</td>
<td>Multispectral</td>
<td>20 m</td>
<td>R, G, &amp; IR bands, 0.50 – 1.73 µm</td>
</tr>
<tr>
<td>SPOT 5</td>
<td>Panchromatic</td>
<td>5 m</td>
<td>0.51 – 0.73 µm</td>
</tr>
<tr>
<td>SPOT 5</td>
<td>Multispectral</td>
<td>10 m</td>
<td>R, G, &amp; IR bands, 0.50 – 1.73 µm</td>
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All images evaluated with spatial resolutions ranging from 5 to 20 meters successfully displayed the water surfaces of the pools to varying degrees of clarity (Figure 26). The presence of water can be seen in all the images, and surface area can be measured using the polygon measuring tool in ArcMap 10. Although the spatial resolution is 5 m better for the panchromatic images, differentiation between bare basin and water surface reflectance can be difficult in them due to the limited spectral resolution, which is not the case with the multispectral images (Figure 26 and Figure 27). Additionally, since the reflectance of the water of the panchromatic images is gray-scale and the same as many other surfaces in the image, the process of extracting the surface area boundaries cannot be automated.

The temporal resolution of the images available for the study area is inconsistent and unpredictable (data access given through EarthExplorer, 2012). The most frequent images available for the study area during 2011 without interfering cloud cover were taken by SPOT 5, which also provides the best spatial resolution. The temporal change of a vernal pool can be monitored using SPOT 5 images, as demonstrated with one vernal pool from July 29, 2011 to August 29, 2011 (Figure 27). When comparing the SPOT 5 panchromatic and multispectral images for August 29, 2011 (Figure 27), it is somewhat unclear where the water is in the panchromatic image. The blue color of water reflected...
in the multispectral image clarifies that the water is only located inside the dugout in the basin, providing a good visual demonstration of the water change. The analysis of change of the two multispectral images shows a dramatic decrease of water from July 29, 2011 to August 29, 2011, indicating a decrease in water availability to wildlife and cattle, and a possible concentration of water contaminants during that time. Due to the limitations of the other images, SPOT 5 multispectral 10 m images were selected for refining the quantification method, as they are the best choice for analyzing vernal pool water quantities for the low vegetation area of interest.
Figure 26. Comparison of various high spatial resolution images of Hart Mountain vernal pools, from left to right, top to bottom: ASTER 15 m resolution; SPOT 4 panchromatic 10 m resolution; SPOT 4 multispectral 20 m resolution; SPOT 5 panchromatic 5 m resolution; and SPOT 5 multispectral 10 m resolution.
Figure 27. Temporal change of a large vernal pool called Benjamin Lake, from July 29, 2011 (left image) to August 29, 2011 (last two images) using SPOT 5 data. The middle image shows the 5 m resolution panchromatic image on August 29, 2011, and the last image show the 10 m multispectral image taken at the same time. Note the presence of water is only located inside of the dugout in the basin in the August 29, 2011 image.
Two additional SPOT 5 multispectral images show representative vernal pools full of water on May 1, 2011, then present only in the dugout portions of the basins on July 29, 2011 (Figure 28).

In general, water is best differentiated from land in the 0.74 – 2.50 µm near-infrared and middle-infrared regions of the electromagnetic spectrum (Jensen, 2007). The peak reflectance of water with clayey suspended sediments has been shown to be in the range of 0.65 – 0.70 µm (Jensen, 2007). The SPOT 5 images used are multispectral with red, green and blue bands in the range of 0.50 – 0.89 µm, with a 10 m resolution, and a short wave infrared (SWIR) band with 1.58 – 1.75 µm spectral resolution and 20 m spatial resolution that is re-sampled to 10 m. Metadata for the images are downloaded as part of the download package, and state many details of the acquisition, processing, calibration, position of satellite (e.g., angle of incidence, sun azimuth, sun elevation, altitude), cloud cover percent, map projection and datum, and more. The SPOT 5 images were downloaded in USGS L1T bundle format, resulting in GEOTIFF image files.
Analysis:

The spatial extent of the SPOT images were clipped to a polygon to remove the boundaries of the image, where the image meets the black no-data values, which is problematic for the Maximum Likelihood Classification tool, and to remove large areas that are not part of the study area, or are not high desert. Images that are used for temporal comparison were clipped with the same polygons so the range was the same, for appropriate statistical comparisons.

The various high desert surface areas in the SPOT 5 images produce a wide variety of reflectance values received by the satellite sensors. Each pixel in the image has four values, one for each band, and combined is known as the spectral signature of the pixel (Kashaigili et al., 2006). In order to derive the surface areas of the vernal pools from the images, the pixels must be reclassified into their respective surface types based on their spectral signatures. For the purpose of this study, the only two classifications that are relevant are water and not water. It is therefore appropriate to use a supervised classification method, rather than an unsupervised method (Ranade and Irmak, 2010). To do this, representative pixels of water must be manually selected for each image through the Training Sample Manager in ArcGIS 10. Representative samples of all other landforms were also selected and grouped together as a “non-water” classification. The number of classifications, from a few to many, is determined by the user in the Training Sample Manager. The reflectance values of each representative pixel are on four scatter plots of each band plotted against each other, and are color coordinated to show which surface type each point belongs to. The scatter plots allow visualization of the separability and distribution of the training samples. The more differentiation (i.e., less overlap) for each type of surface in the scatter plots, the better the quality the classification will be. The

---

7 Representative pixels can be selected from one image, then used to analyze subsequent images, but the quality of the resulting classifications is higher if representative pixels are selected from the correlating image (i.e., the error is higher if one classification signature file based on a single image is applied to other images).
resulting scatter plots show spectral signature resolution from the supervised classification of the pixels (Figure 29).

Figure 29. ArcGIS 10 view of a manual classification of representative pixels for water (yellow), bare basin (blue), typical high desert (pink), no data values (green) and agriculture fields (brown) for the image layer (on the right), and the resulting scatter plots of unique band combinations (i.e., spectral signatures) (on the left). Each dot represents a single pixel’s band reflectance values. Note that only water and non-water classifications will be identified for vernal pool surface area classification; image above is for demonstration purposes.

The identified spectral signatures are saved as a spectral (.gsg extension) file. The spectral file, along with the clipped SPOT 5 image file meant to be re-classified, are then analyzed using the Maximum Likelihood Classification tool. The analysis results in a reclassified raster file where each pixel in the image file is identified as whichever surface type is statistically most likely based on the representative pixels. When classifying for only water and non-water, the resulting raster file has only these two types of pixels.

The classified raster file is then converted to a polygon shapefile with the Raster to Polygon tool. Because of the two-toned nature of the raster, the result
is a feature layer contained only of polygons of the water bodies in the extent identified, and one single polygon of non-water.

The surface areas of the vernal pools are then quantified from the polygon feature layer by using the Calculate Areas tool. A layer is then created with the pool areas printed to the attribute table. The large polygon of everything other than water is easily identified and removed due to its extremely large size in comparison. The Model Builder model of this analysis procedure was standardized and tested (Figure 30).

**Figure 30.** Model Builder screen shot for July time point analysis. The numbered names of the two input files (.TIF image file and .gsg spectral signatures file) are the standard naming system for SPOT image files (the date is contained within), and was preserved for source and tracking assurance.

Automation of this analysis, extraction and computations on the data will provide as an immense time saver, as the interest in vernal pools monitoring is across a wide range of space and time. For this reason, the Python code was extracted from the Model Builder window, edited and expanded on so that it would run the analysis for two images at two points in time, extract the vernal pools’ surface areas from the attribute tables of the resulting layers, subtract the one non-water polygon, and calculate basic statistics on them (e.g., maximum, minimum, total and average surface areas for each point in time, and percent
change of total surface area from time one to time two). The code then prints the statistics for the two time points to a .csv file, which can be opened with Excel.

3.4. Results and Discussion

The July 29th, 2011 and August 29th, 2011 image files from the study area were successfully run through the Model Builder model, and through the Python code. The spectral signature scatter plot shows areas of segregation between water and non-water reflectances for many of the pixel band combinations, and some overlap between the two categories in some pixel band combinations (Figure 31). The full sized and zoomed in views of the original SPOT 5 image and the resulting layers for the July 29th 2011 analysis are shown in Figure 31 through Figure 35.

The Maximum Likelihood Classification tool appropriately produces a raster with all pixels re-assigned to be water or non-water (Figure 33). The Raster to Polygon analysis turned the water pixels into polygons (Figure 34). After using the Calculate Areas on the polygons, the resulting layer has the areas of the pools printed in the attribute table (Figure 35).

Figure 31. Spectral signatures scatter plots for water (blue) and non-water (yellow).

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8 The Python code used for automation of this analysis is presented in Appendix 5.5.
Figure 32. Original SPOT 5 image at the full extent (left) and zoomed in on a representative pool (right).

Figure 33. Resulting raster views after the Maximum Likelihood Classification with pixels re-assigned as water (blue) or non-water (peach).
At the completion of the Python code run using the two original SPOT 5 images and the two spectral signature files, the results were successfully printed out to a .csv file in the specified folder. The .data show a dramatic change of the total surface area of water in the study area between July 29, 2011 and August 29, 2011, from 2,264,977 to 758,730 m² (Table 4).
Table 4. Resulting data printed to the .csv file from Python code that runs the analyses in ArcGIS and computes statistics on the two time points.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Water Surface Area, m²</td>
<td>2264977</td>
<td>758739</td>
<td>-199</td>
</tr>
<tr>
<td>Minimum Surface Area, m²</td>
<td>68</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Maximum Surface Area, m²</td>
<td>466655</td>
<td>324145</td>
<td></td>
</tr>
<tr>
<td>Average Surface Area, m²</td>
<td>12243</td>
<td>4386</td>
<td></td>
</tr>
<tr>
<td>Median Surface Area, m²</td>
<td>473</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>Surface Area Standard Deviation, m²</td>
<td>52496</td>
<td>26956</td>
<td></td>
</tr>
</tbody>
</table>

Validation

The surface area of the large vernal pool (Figure 31 through Figure 35) was calculated again for July 29th, 2011, this time manually using the polygon measuring tool in ArcGIS. The result was compared to the result computed by the model for validation purposes. The results were a 2.4% difference (Table 5).

Table 5. Model validation of surface area computations of a vernal pool by model results compared to manual delineation using the polygon measuring tool.

<table>
<thead>
<tr>
<th>Polygon Measuring Tool - m²</th>
<th>Model - m²</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>455,732</td>
<td>466,655</td>
<td>2.4 %</td>
</tr>
</tbody>
</table>

The model estimation of the water boundary is likely more accurate than the polygon measuring tool, depending on how long you took to draw the perfect polygon. You can also see simply by visual comparisons of original and classified images that the model works very well for identifying surface areas by this method (Figure 36).
Discussion

Although the method efficiently derives surface water area across a defined region, it does not differentiate vernal pool surface water from other surface water types. In many regions of Oregon’s high desert, vernal pools and dugouts are the sole source of surface water, such as near Fredrick Butte. Regional knowledge can be applied to reduce quantification of non-vernal pool surface areas. SPOT images can be clipped to smaller regions of interest as needed. Even if the process includes surface area change of non-vernal pools, the overall change in surface area in the region will still provide valuable information on the status of the vernal pools nearby, as they are likely undergoing similar changes. This is particularly true in Oregon’s high desert, where the boundaries of even the largest lakes retreat significantly in most summers.
Potential Sources of Error

Due to the extremely small size of some vernal pools and the 10 m resolution of the SPOT 5 images, some smaller pools can be under-classified, resulting in a bias toward less water availability than is actually the case. This is acceptable for our purposes as vernal pools are typically in the range of 1 m$^2$ to over 4 km$^2$ (Christy, 2012), so the amount of water that is not being included due to this error is relatively small.

The analysis method is limited by the temporal resolution of the SPOT 5 multispectral images. Temporal resolution availability through the USGS government license is inconsistent and unpredictable (i.e., not all images acquired by each satellite are available through the portal). There is potential to use SPOT 4 multispectral 20 m data to augment the temporal resolution, but the coarser spatial resolution would further limit the ability to delineate small pools, and robust data comparison and error analysis must be conducted as images of the same kind should typically be used to adequately analyze change and minimize errors. Other satellite images may be used also, although the success is limited by the spatial, spectral and temporal resolution of the satellite images. Depending on this method for clarification of seasonal status of the vernal pools is somewhat vulnerable in this sense, and extrapolations to various times of the season may be necessary.

The quality of the ArcGIS classification is given by the resolution of the scatterplots that show the typical reflectance signatures of the land classifications identified, in this case for “water” and for “non-water” (Figure 31). If there is clear segregation in the scatterplots, the statistical significance is higher. The inherent variable nature of the vernal pools complicates the method because the reflectance of small, flat, shallow pools is quite different than that of deeper pools. There is much less surface area of the small pools, and so there are less representative reflectances to inform Arc that this is also water (e.g., a couple hundred pixels per SPOT 5 image). The large number of other pixels representing deeper water and non-water (tens of thousands of pixels) may overpower the statistical classification of the tool. Although less representative
pixels could be chosen for large pools and non-water, this would increase the odds of the tool erring in the favor of over-classifying water. Although the spectral resolution between water and non-water is not completely separate on the scatter plots (e.g., for shallow pools and wet agricultural fields), the method still has worked for every spot check done, and as indicated in the validation section.

3.5. Conclusion

The method successfully extracts timely water surface area information of the changing Oregon's high desert vernal pools in an extremely efficient manner compared to field measuring. The SPOT 5 multispectral 10 m images can be monitored to determine the presence of water, to save time and gas that would otherwise be wasted visiting dry basins. The calculated areas of the polygons can be utilized to find specific vernal pool water surface areas by using the identify function and clicking on a vernal pool polygon. The Python code can be used to quickly and effectively determine the overall change in available water over two time points in a large area in the semi-arid environment, by simply feeding the image and signature files into it. Although there are a few potential sources of error, they are minor and manageable through validation processes. Given the shallow and flat nature of vernal pools, surface area is considered an adequate representation of overall water availability, and this is considered a solid first step toward utilizing this method in characterizing the seasonal status of Oregon's high desert vernal pools.

Future

The method has potential to be improved so that a third dimension is included in the water quantification analysis, by incorporating an adequate Digital Elevation Model (DEM) that penetrates the vernal pools (e.g., bathymetric LIDAR) to use with surface area to calculate volume. Water change analysis does not account for topographical variability of the pool floors in the water quantity calculation, and therefore assumes shallow, flat pools in order to be
used for water quantity assumptions. Since the majority of the pools are in fact flat and shallow, this is not an unreasonable assumption to make. However, integrating the 3rd dimension would remove this error and improve future uses of the method. A DEM could be used for this purpose. However, given the extremely turbid nature of the vernal pools, remotely sensed data such as lidar may not be able to penetrate the water column, and DEMs might have smoothed surfaces over the pools, making this type of analysis moot.

Correlations between water quality data collected in the field and water quantity data extracted from this method could potentially be performed for seasonally dependent parameters. Predicting water quality information of the vernal pools solely from the SPOT images could be validated by testing predictions on past images and gathered water quality data not used in method development. This would save an unfathomable amount of time and money for managers to monitor these systems.
3.6. References


CONSIDERATION OF CLIMATIC INFLUENCES ON WATER AVAILABILITY IN OREGON’S HIGH DESERT VERNAL POOLS

Sara A. Wyland
4. CONSIDERATION OF CLIMATIC INFLUENCES ON WATER AVAILABILITY ON OREGON’S HIGH DESSERT VERNAL POOLS

4.1. Abstract

Vernal pools vary greatly in their distribution, hydrology and hydrologic connectivity (seasonally and spatially). Since hydrology is the driving force for ecologically important functions of vernal pools, it is important to understand controlling factors of water quantity. This study was conducted to assess for correlations between local climate data and surface area water quantity in a small region of Oregon’s high desert. A GIS and remote sensing method was used to extract total surface area of water in the region at ten different time points over 2010 through 2013 using SPOT 4 and SPOT 5 images. Climate data was gathered from local RAWS and SNOTEL weather stations. Preliminary data suggests multiple-year persistence of high or low precipitation is a driving factor in surface area quantities, particularly for the larger basins. Analysis of additional time points of water surface areas is needed to firmly draw conclusions about surface area quantity causation. Comparison of climate data from 1913 to 1960 and 1987 to 2012 show 45% less average annual precipitation in recent years. If climate change persists in the region, vernal pool surface areas will likely be impacted.


4.2. Introduction

Vernal pools are surface water wetlands that undergo an annual cycle of filling, ponding, drying, and desiccation. The duration of ponding typically lasts for a few weeks to a few months, depending on the water holding capacity of the soil, position in the landscape, precipitation and evapotranspiration rates (between and within years) and depth of the depression (Bauder, 2005; Robins...
and Vollmar, 2002). The unique hydrological regime leads to ecologically important functions, such as serving as breeding and rearing grounds for many species, and they tend to become isolated micro-regions of high biodiversity. The reliable returning presence of water to a vernal pool bed is the defining character that allows specialized and unique biota to develop, and discourages upland plants from encroaching (Williamson et al. 2005; Zedler, 2003). The wetland plant species that inhabit the vernal pools will vary also with duration of ponding. For example, facultative-wet or obligate plants will be more correlated with vernal pools with longer hydroperiods than shorter (Adamus, 2006). Bliss and Zedler (1998) showed that vernal pool specific species tend to not germinate under un-favorable conditions (temperature and precipitation timing), and therefore may not be resilient to climate change, giving generalizing species a higher competition factor.

Hydrologic connectivity can be an important driver of vernal pool water chemistry, biodiversity, vegetation structure and net primary productivity (Cook and Hauer, 2007). Loss of vernal pool connectivity can also lead to amphibian declines due to their pool and overland dispersal behaviors, and a decline in their connections to other populations (Compton et al. 2006; Semlitsch and Bodie, 1998). Therefore, their ability to withstand stochastic fluctuations is decreased, demonstrating the importance of looking at vernal pools on multiple scales (Compton et al. 2006; Oscarson and Calhoun, 2007).

Lengthening the duration of water ponding by partial excavation of vernal pool basin to and to act as a stock pond is common (Clausnitzer and Huddleston, 2002). Increased ponding duration could lead to increased range of large herbivores (livestock and native) later into the year, into areas they would typically not go due to lack of water (Clausnitzer and Huddleston, 2002; Landsberg et al. 1997). The establishment of aquatic plants could also occur, and encourage proliferation of predaceous aquatic insects, and reduce native and unique species (Clausnitzer, 2000; Clausnitzer and Huddleston, 2002; Graham, 1997; Roth and Jackson, 1987; Weir, 1971). Vernal pool ponding duration is likely sensitive to climate variability due to the ephemeral nature.
The semi-arid climate of Oregon’s high desert has long, severe winters and short, dry and hot summers. Specific temperature and precipitation are spatially and temporally variable, in part due to the high intensity, low range storms that occur in the high desert. Great fluctuations between drought and high precipitation often occur (Dlugolecki, 2010). In the Hart Mountain Antelope Refuge, January temperatures range from -16 to 9.7 °C on average, and July temperatures range from 9.2 to 28.3 °C on average (Western Regional Climate Center, 2013). Precipitation is usually 150 to 300 mm per year, with most of that falling as snow from November through March, then as rain from March through May (Western Regional Climate Center, 2013).

Most vernal pools Oregon’s high desert appear very hydrologically isolated from each other. The exception to this is the Warner Valley Wetlands at the base of Hart Mountain. The area consists of a distinct mosaic of small and large wetlands where the surface water is clearly connected in the wet part of the year. As the season dries, the pools shrink and the surface water disconnects, and the pools dry out in order of smallest to largest size (Figure 37). The largest of the ponds do not completely dry out in most years (although they do in many), and are therefore are considered year-round wetlands rather than vernal pools.
Figure 37. Change of Connectivity in Warner Valley Wetlands as they Dry

Although the bankfull surface water boundaries in Oregon’s high desert have been extensively mapped on high resolution road atlases and the National Wetlands Inventory (NWI), details of temporal variability of surface areas is unknown. Information about water quantity allows us to understand water availability for wildlife and livestock, temporal variability of water sources, and how water quantity and water quality parameters are correlated. Vernal pools were visited in Oregon’s high desert from July through September of 2011, and February through September of 2012. It was not feasible to monitor the water quantity of the pools during field visits, as it changes greatly over time and the process of measuring water quantity is extremely time consuming. Previous
studies have shown that remotely sensed images can be used to aid in mapping vernal pool water quantities (e.g., Lathrop et al., 2005, Kashaigili et al., 2006, Hass et al., 2009), although published work of this type is limited and does not include the Northern Great Basin. Determination of water surface areas can be used as a general measure of the overall change of vernal pool water availability.

Since Oregon’s high desert is semi-arid, the water in vernal pools in the region are an important contribution to the total water availability. The amount vernal pools contribute is extremely variable over time due to their hydrologically ephemeral nature and sensitivity to weather variations. The hydroperiods of vernal pools in Oregon’s high desert, or the factors that control them, have not been broadly evaluated.

Bauder (2005) found that the total amount of precipitation in a year is the primary determinant of the hydroperiod of vernal pools in California, but it is also affected by the pattern and intensity of storms. Bauder’s results suggest more intense and closer together storms lead to longer inundation periods than the same amount of precipitation spread out over a longer period in normal years, the opposite was true during dry years (ponding was longer when rainfall was temporally distributed as opposed to concentrated), and precipitation timing concentration over a year had no effect during wet years.

This study was designed to evaluate how the water availability in Oregon’s high desert changes over time, and to look for correlations in recent climate patterns and water quantity. Past data may reveal a correlation between climate and water availability, which can then be used to aid in understanding how possible future climate scenarios would affect the vernal pools. Since vernal pools are so inconsistent, climate change affects are likely. Ecological implications of changing water availability in the region could be severe, particularly with respect to changing competition dynamics between users.

4.3. Materials and Methods

SPOT 4 and SPOT 5 multispectral images were used to classify surface water of vernal pools at different time points in the same region covering
approximately 2,100 km² range, from the top of Hart Mountain west through the Warner Valley Wetlands to the top of Abert Rim, with elevation ranging from approximately 1,400 m to 1,900 m (Figure 38). The irregular polygon shape of the study area was created to eliminate problematic no-data SPOT borders, and areas difficult for the software to classify, such as the west-facing slope of Hart Mountain. All of the images analyzed were clipped to this exact same extent, using the Extract by Mask tool. SPOT 4 and 5 images are available through the USGS commercial data buy starting in 2010. Images were selected based on several criteria; that there was less than 10% cloud cover, that there was not any snow in the vernal pools, as it is indistinguishable from snow on the ground, and that it covered the region of interest entirely. The best temporal resolution that could be obtained from both images under this criteria was ten total, from July 2010 to April 2013.

Figure 38. Approximate Location of Study Area (left) and Actual Study Area Polygon Used in Analysis.

It is not typically appropriate to conduct temporal remote sensing analysis using more than one satellite. However, SPOT 4 and SPOT 5 multispectral images have identical spectral resolutions, and the only major difference between them is SPOT 4 has a lower spatial resolution. The result of this is the ability of SPOT 5 to classify smaller vernal pools than SPOT 4. Since this would
bias temporal quantity analysis across the image types, the SPOT 5 data were amended to exclude all pools smaller than the minimum detectable by SPOT 4. The result was identical spatial capabilities for appropriate change analysis.

A python tool was developed to automate processing the images (Appendix 5.5). The tool clips the raster images to the polygon shown (Figure 38), conducts a supervised classification of the raster cells to be water or non-water, converts the rasters to classified polygon shapefiles, removes the non-water and SPOT 5 image polygons smaller than detectable by SPOT 4, calculates the areas of the remaining pool surfaces, prints them to an attribute table, calculates basic statistics on the surfaces, calculates percent change over two time points, and prints the statistics to a local .csv file.

Precipitation, temperature and solar radiation data was gathered from the Rock Creek remote automated weather station (RAWS) located on top of Hart Mountain inside the study area (119° 39' 21" W; 42° 32' 53"N). Time series climate data was compared to the water availability extracted from SPOT images during the time points of data access. Although SPOT data was only available for ten times during 2010 through 2013, time series climate data was considered for 2006 through 2013, to look at long term influences on water quantities.

SNOTEL data was gathered from the three closest locations, which form a triangle around the study area. The sites are SILVIES, 83 km NE from the RAWS location and the study site (118° 41' W; 42° 45' N), Summer Rim, 53 km west of the western edge of the study site (119° 32' W; 43° 57' N), and Snow Mountain, 124 km north of the northern edge of the study site (118° 41' W; 42° 45' N). The elevation of the SNOTEL stations are 2,153 m, 2,158 m and 1,899 m, and the elevation of the RAWS site is 1,716 m. The snow water equivalent recorded at these stations were averaged.

### 4.4. Results and Discussion

The total water surface quantity in the study area was extremely low at the first image date in 2010, and remained low into early 2011 (Table 6). After the
pools greatly refilled by August 2012, the percent change remained much more consistent into 2013.

Table 6. Total Water Surface Area during Image Dates and Percent Change

<table>
<thead>
<tr>
<th>Image Date</th>
<th>Total Water Surface Area, km²</th>
<th>Percent Change from Previous Time Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 15, 2010</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>September 23, 2010</td>
<td>0.9</td>
<td>-83%</td>
</tr>
<tr>
<td>October 19, 2010</td>
<td>1.1</td>
<td>+23%</td>
</tr>
<tr>
<td>February 2, 2011</td>
<td>11.9</td>
<td>+978%</td>
</tr>
<tr>
<td>August 12, 2011</td>
<td>62.5</td>
<td>+423%</td>
</tr>
<tr>
<td>December 4, 2011</td>
<td>48.8</td>
<td>-22%</td>
</tr>
<tr>
<td>January 30, 2012</td>
<td>67.3</td>
<td>+38%</td>
</tr>
<tr>
<td>February 12, 2012</td>
<td>48.8</td>
<td>-27%</td>
</tr>
<tr>
<td>May 31, 2012</td>
<td>47.2</td>
<td>-3%</td>
</tr>
<tr>
<td>April 4, 2013</td>
<td>35.2</td>
<td>-23%</td>
</tr>
</tbody>
</table>

The annual precipitation in 2006 through 2009 was 192, 170, 155, and 257 mm, respectively (Figure 39). The precipitation in 2010 through 2012 was 246, 158 and 176 mm, respectively (Figure 40). Solar radiation data were not collected at the RAWS until Fall, 2010.
Figure 39. Climate Data for Study Area in 2006 through 2009.
Temperature shown is a 7 day moving average of the average daily temperatures. Climate data from Western Regional Climate Center, 2013.
Figure 40. Climate Data and Total Water Surface Area for the Study Area in 2010 through 2013.
Temperature shown is a 7 day moving average of the average daily temperatures. Climate data from Western Regional Climate Center, 2013.
The total precipitation was highest in 2009 and 2010; 257 mm and 246 mm, respectively, while it was below 200 mm in all other years. Interestingly, 2010 had the lowest available surface water by far. Although the Geographic Information System (GIS) analysis couldn’t be performed on Landsat multispectral (MSS) due to conflicting spatial and spectral resolutions, and the scan line corrector failure that occurred with the Landsat 7 satellite, the high spectral images were individually viewed for water presence in the study area prior to the summer of 2010. Landsat data clearly shows that the large Warner Valley Wetland basins started to dry in August 2008, likely the result of consecutively low precipitation in 2006 through 2008. The basins did not refill back to their regular stage until spring of 2011. Although total annual precipitation in 2011 was also below 200 mm, almost all of it fell in the spring. It is possible the refilling was the response of two and a half years of consecutively high precipitation from 2009 to mid-2011. Since mid-2011, precipitation has again fallen to similar values seen in 2006 through 2008, and the April 2013 data shows the lowest surface area levels since early 2011, again indicating a response to a two to three year consecutive trend.

Climate data was recorded at Valley Falls, just south of Lake Abert at 1,318 m elevation from 1931 to 1960. The Valley Falls station lies just southwest of the study area, and 52 km from the Rock Creek RAWS, which is at 1,715 m elevation. The average annual precipitation from 1931 to 1960 was 314 mm, with a range of 163 mm to 469 mm (Phillips and Denburg, 1971). The average annual precipitation from 1987 through 2012, excluding June 1995 through May 1996 due to missing data, was 199 mm, with a range of 95 mm to 413 mm (Western Regional Climate Center, 2013). Interestingly, average temperatures were slightly less in the more recent time range (Table 7).

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9 Data from 1961 through 1986 was not available.
Table 7. Comparison of Temperature and Precipitation in Two Distinct Time Periods

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-1.3</td>
<td>-0.4</td>
<td>35.8</td>
<td>9.9</td>
</tr>
<tr>
<td>February</td>
<td>0.6</td>
<td>-0.3</td>
<td>33.3</td>
<td>7.0</td>
</tr>
<tr>
<td>March</td>
<td>3.4</td>
<td>2.3</td>
<td>28.4</td>
<td>13.7</td>
</tr>
<tr>
<td>April</td>
<td>7.3</td>
<td>4.9</td>
<td>24.4</td>
<td>32.3</td>
</tr>
<tr>
<td>May</td>
<td>10.9</td>
<td>9.4</td>
<td>36.3</td>
<td>38.2</td>
</tr>
<tr>
<td>June</td>
<td>14.3</td>
<td>13.9</td>
<td>35.1</td>
<td>27.4</td>
</tr>
<tr>
<td>July</td>
<td>18.8</td>
<td>19.6</td>
<td>7.6</td>
<td>8.5</td>
</tr>
<tr>
<td>August</td>
<td>17.7</td>
<td>18.7</td>
<td>7.4</td>
<td>9.3</td>
</tr>
<tr>
<td>September</td>
<td>13.7</td>
<td>14.5</td>
<td>14.5</td>
<td>12.9</td>
</tr>
<tr>
<td>October</td>
<td>8.8</td>
<td>8.2</td>
<td>28.2</td>
<td>18.6</td>
</tr>
<tr>
<td>November</td>
<td>3.1</td>
<td>2.1</td>
<td>25.1</td>
<td>16.1</td>
</tr>
<tr>
<td>December</td>
<td>0.3</td>
<td>-1.3</td>
<td>38.1</td>
<td>10.5</td>
</tr>
<tr>
<td>Year Average</td>
<td>8.1</td>
<td>7.6</td>
<td>314</td>
<td>199</td>
</tr>
<tr>
<td>Percent Difference</td>
<td>6%</td>
<td></td>
<td>45%</td>
<td></td>
</tr>
</tbody>
</table>

Percent difference = difference / average * 100

The percent difference was calculated rather than the percent change because the data were not collected from the same station or elevations. Even so, the areas are close enough to expect similar climate. Although temperature differences show a lower temperature for the recent time period, this may have more to do with the recent data being collected at a higher elevation. Climate change could cause an increase in temperature in the region. Much of the precipitation in the area falls as snow (Figure 41). If temperatures increase, the amount of precipitation that falls as snow will be reduced, and the timing and frequency of rain events may change. Heavy rainfall as opposed to slowly melting snow could change the ponding dynamics of the vernal pools, such as more frequent flooding and shorter hydroperiods that would otherwise be
sustained by snowmelt. Temperature increases also lead to higher losses from evaporation, which could have significant implications for the water limited area. Whether or not climate change explains the 45% difference in annual precipitation is unknown, but the difference is great enough to cause concern.
Figure 41. Snow Water Equivalent, Precipitation and Water Surface Area for the Study Area in 2010 through 2013.
Precipitation data from the Western Regional Climate Center, 2013. Snow data from the Natural Resources Conservation Service, 2013. Snow water equivalent shown is a 7 day moving average of the daily snow water equivalent.
Future

Although SPOT 4 data exists back to 1998, the USGS data buy available to government employees and contractors only includes images starting in 2010. Unfortunately, SPOT images cost about $2,000 per image. Gaining access to SPOT 4 images between its launch in 1998 and 2010 to increase the temporal resolution of the method would lead to a clearer understanding of correlations between climate and water quantity in Oregon’s high desert.

4.5. Conclusion

More appropriate satellite data is needed to increase the temporal resolution of water surface areas for looking at long term trends. Resolute conclusions cannot be made, but preliminary analysis suggests the available surface area of vernal pool water in Oregon’s high desert is dependent on total annual precipitation and persistence of the climatic pattern.

Precipitation in the region was significantly lower from 1987 to 2012, than was recorded for 1913 to 1960. Since water availability is likely dependent on annual precipitation, it is assumed that the available water is also lower in recent years than before. If climate change increases temperature in the region, it is likely that more snow will fall as rain, evaporation rates will increase, vernal pool ponding dynamics will be altered, and available surface water will decrease quicker into the season.
4.6. References


5. APPENDICES

5.1. Appendix 1 – GIS Analysis of NWI Data for Study Area

The following steps were performed to analyze NWI data in Harney and Lake Counties:

1. Selected all polygons from the NWI that intersected with Harney County, and exported the data to a new shapefile: Harney_County_NWI_Wetlands
2. Selected all polygons from NWI that intersected with Lake County, and exported the data to a new shapefile: Lake_County_NWI_Wetlands
3. In the Harney_County_NWI_Wetlands shapefile, clicked on “Select by Attributes”. Created the following SQL expression to select all of the wetland types that are Palustrine: "ATTRIBUTE" LIKE 'P%'. Result = 18,777. Further narrowed the selection to remove wetlands with the codes for permanently flooded and artificially flooded: Select By Attributes → Remove from current selection, with the SQL expression: "ATTRIBUTE" LIKE '%H' OR "ATTRIBUTE" LIKE '%K' OR "ATTRIBUTE" LIKE '%H%' OR "ATTRIBUTE" LIKE '%K%'. Result = 17,919. Exported results to a new shapefile named Harney_County_NWI_Palustrine.
4. Repeated the step above with the Lake_County_NWI_Wetlands shapefile and named the result Lake_County_NWI_Palustrine. Result = 27,596
5. Selected from the palustrine shapefiles the wetlands that have been determined to be altered based on the Diked/Impounded (h), Partially Drained/Ditched (d), Artificial (r), Spoil (s) or Excavated (x) subclass (Beaver alterations (subclass b) were left in as they are considered natural): "ATTRIBUTE" LIKE '%h' OR "ATTRIBUTE" LIKE '%d' OR "ATTRIBUTE" LIKE '%r' OR "ATTRIBUTE" LIKE '%s' OR "ATTRIBUTE" LIKE '%x'. Once the selections had been made, exported the selections to shapefiles Harney_Palustrine_Altered and Lake_Palustrine_Altered.
The following steps were performed to get a better idea of the number of vernal pools in the study area, by dissolving the boundaries that are touching:

1. Selected all polygons from the NWI that intersected with the study area, and exported the selection to a new shapefile called NWI_Study_Area.
2. Selected all of the polygons then removed from the current selection all polygons that were riverine: "ATTRIBUTE" LIKE 'R%', and exported to a new shapefile called NWI_StudyArea_Pools.
3. Selected all of the polygons then removed all of the large lakes: “ACRES” > 7000, and exported to a new shapefile called NWI_StudyArea_Pools_Fin.
4. Merged the remaining polygons with touching boundaries into single polygons using the Dissolve tool with the “Create multipart features (optional)” box unchecked, and saved the shapefile as NWI_SA_VPs_Dissolved.

The following step was performed to extract the number of excavated pits in the study area:

1. From the NWI_StudyArea_Pools_Fin shapefile, selected from the current selection all polygons that had the partially drained/ditched (d), diked/impounded (h), artificial substrate (r), spoil (s) or excavations (x): "ATTRIBUTE" LIKE '%h' OR "ATTRIBUTE" LIKE '%d' OR "ATTRIBUTE" LIKE '%r' OR "ATTRIBUTE" LIKE '%s' OR "ATTRIBUTE" LIKE '%x'.

:
5.2. Appendix 2 – Water Quality QA/QC Protocols

The following instructions describe the key processes followed while performing water quality analyses on Oregon’s high desert vernal pools. Consistency in processes and quality validations were prioritized for data reliability. All critical activities, observations, dates and times were documented in field notebooks. A separate notebook was maintained for all equipment-related activities.

**Bottle and Filtration System Acid washing**

Grab samples are taken for Ion Chromatography (IC) analysis. All materials that come in contact with the sample are acid washed according to these instructions prior to contact. Consistency in the procedure provides assurance of the removal of contaminants from representative bottle blank analysis. The bottle blank analysis validates the acid washing procedure. Newly purchased bottles and previously used bottles are treated the same prior to use. The standard sample bottle used is a 125 mL HDPE Nalgene bottle.

Rinse the bottles with DI water or 10% (v/v) HCl, partially fill individual bottles with the appropriate solvent (about 1/3 to 1/2 full), cap, and vigorously shake for at least 2 minutes. For the acid rinse, pour the acid back into the appropriate vessel (do not dump down the drain). New 10% (v/v) HCl is prepared as needed whenever the acid becomes cloudy or contains particulates. After the DI rinse, dispose of the water. When performing an overnight soak, fill the bottles as completely as possible (i.e., to the brim), and cap tightly.
Rinse the bottles in the following sequence:

1. DI water rinse
2. 10% (v/v) HCl rinse
3. DI water rinse
4. DI water rinse
5. DI water overnight soak
6. DI water rinse

The bottles must be completely dry before capping to ensure mildew does not grow. Place the cleaned bottles in a very clean environment. Place fiber-free clothes (such as Kim Wipes) across the tops to prevent particles from entering while they dry. Let dry for at least a day before capping.

**Equipment calibration and audits**

A YSI 6920-V2 Multiparameter water quality sonde is used for field sample collection. The sonde measures water quality parameters temperature, specific conductivity, pH, oxidation-reduction potential, turbidity and dissolved oxygen (percent and mg L\(^{-1}\)). Additionally, resistivity, salinity and total dissolved solids are calculated from the conductivity reading. Operation, maintenance and calibration procedures must be done according to the manufacture’s equipment manual. More frequent calibrations lead to more accurate results, although this particular sonde has very little drift. Calibrations are usually conducted between each sampling session, and must be conducted at least every 2 months when in use.

Post-sampling audits are performed after each sampling session to validate sonde stability and performance (i.e., accuracy). Conductivity, pH, ORP and turbidity audits are conducted by comparing the sonde readout of standard solutions to the known standard values. The DO audit is conducted by comparing the sonde readout of environmental water to a Winkler titration, per Upper Deschutes Watershed Council SOP (UDWC, 2008).
Important note: When calibrating the sonde, enter the standard values manually corrected for the current temperature. When auditing parameters, the readings are already temperature corrected.

**Field sampling**

Field sampling is done in a way to minimize sampling error. Sampling was always performed when there was no precipitation occurring. Agitation of the pools must be kept to a minimum while samples are collected. An extension rod and accompanying stand were created in order to sample away from the immediate bank of the pools without wading in them (Figure 15).

While this works well for the dugouts, it is usually impossible to sample the natural pools without wading into them, as the outer perimeters of the pools are often too shallow and the change in slope is too small to reach a good sampling depth without wading in. In these situations wade in, but stand still until particles settle, and the sampling rod is still used.

Remove the calibration cup from the sonde bulkhead, and install the probe guard. Secure the sonde in the 3-prong clamps on the end of the extension rod. Extend the rod to a location deep enough for the sonde bulkhead to be submerged, but not touching the substrate, if possible. Gently lower the sonde into the water, turn the sonde on, clean the DO and turbidity sensor optics with the wiper blades, and wait for the parameters to stabilize. Parameter drift is common, but the rate of drift slows to a steady drift, at which point it is considered “stable”. Parameter drift is worse in windy conditions. Take two sonde points approximately 30 to 90 seconds apart to characterize the stability of the parameters while sampling, and take note of any unusually high drift.

All critical activities are documented, such as the times of sonde sample points. Documenting times is critical in order to be able to cross reference the downloaded data to the appropriate sample location. General observations of the pools are also documented, such as evidence of biological use, ephemeral tributaries, springs, change in conditions, etc. When you return from the field,
download the sonde data to a computer, then transfer to an excel sheet for analysis.

Take a grab sample for IC analysis for anions. Secure an uncapped acid washed bottle to the 3 prong clamp on the extension rod. Rinse the bottle with some environmental water and discard. Lower the bottle upside-down to about the center of the water column. Invert right side-up while under water, so it pulls in water from below the surface. Bring the bottle above the surface before it is completely filled, but is at least half way filled. You must filter and freeze the entire sample collected, and a completely full bottle will expand and warp the sample bottle when frozen. If the bottle comes up full, discard and re-sample. You also do not want to pour water off the top of the sample because you may bias the sample due to settled sediment. Label the sample bottle with the coordinates of the sample collection, the type of sample (guzzler, dugout, altered or natural), and initials and date. Quickly place the sample in a cooler, with ice if possible, and keep cold until filtration is possible. Proceed to filter the sample as soon as possible.

**Sample filtering**

The samples must be filtered down to 0.4 µm before IC analysis. Particles greater than 0.4 µm can damage the IC if injected. Keep samples clearly segregated during filtration (e.g., only have one sample out of the fridge at a time) to prevent sample mix up. Perform the filtrations in a clean environment and be cognizant of potential sources of contamination (Figure 42).
Rinse the filtration system thoroughly (at least 3 times) with DI water, and dry before use. Due to the extremely high turbidity values of many of the vernal pool samples, pre-filtering is recommended to preserve the much more expensive 0.4 µm filters. Typical pre-filters are 40 µm, 5 – 10 µm and 1 µm. Minimize skin contact with the filter to prevent contamination from your skin. Place the filter in the filter housing system, and tighten the threaded attachment piece down as much as possible. Assure the tightening apparatus is strait on the threads and is very tight to prevent sample leakage during filtration. Wet the filter by filtering approximately 10 – 30 mL of DI water through, then dispose of the DI water. Invert the sample several times to suspend any settled sediment in the bottle. Filter the sample with the appropriate pre-filter(s), then return the filtered sample to the sample bottle. After pre-filtering, but before the 0.4 µm filtration, rinse the bottom portion of the filtration system at least 3 times with DI water to remove any particles that may remain from the previous filtration. During the 0.4 µm filtration, rinse the sample bottle at least 3 times with DI water for the same purpose before returning the 0.4 µm filtered sample, or pour the filtered sample
into a new acid-washed bottle. Freeze the sample until IC analysis can be performed. Between samples, disassemble the filtration device and thoroughly rinse each piece at least 3 times with DI water.

Assure a filter blank exists for each filter lot that comes in contact with a sample. Prepare a new filter blank for any new lots used by capturing the filter rinse water in an acid washed bottle, and freeze the sample for IC analysis. Since all filter blanks also come into contact with the filtration system and an acid washed bottle, this blank is considered a blank for all of them, and for the DI water used, and if contaminants are found they may be attributable to any of these materials.

**Nitrates (Anion) Analysis**

The OSU IWW Collaboratory IC is used for anion analysis. The particular interest is in nitrates, although the analysis automatically also gives fluoride, chloride, bromide, phosphate and sulfate. The analysis and equipment maintenance is done according to standard IWW Collaboratory procedures. Quality control checks are run alongside samples. Multiple injections of the same sample validates the IC system. DI water that comes into contact with the bottles and filtration system following the acid washing procedure, and the filters were run to validate the effectiveness of the acid washing procedure, and to verify leachables were not coming from the filters and contaminating the samples.

**QA/QC Data Analysis**

Sample parameter reading accuracy is variable with sonde stability. Grade the accuracy of the field data based on post-sampling sonde audits. Determine this grade from the Accuracy (A) guidelines in the Oregon Department of Environmental Quality’s Data Grade Matrix (Figure 43). Vernal pool data must have at least a grade B to be considered in this study, although this sonde tends to provide grade A+ or A data.
Calculate the difference between the first and second sonde point taken at each site. Either percent difference or absolute difference is used, depending on the parameter and value (use the ODEQ Data Grade Matrix to determine this). Determine the grade of the field measurements from the Precision (P) guidelines in the Data Grade Matrix (Figure 43). Vernal pool data lower than a grade B will be noted in the results. Use the average of the two parameter points for analysis.

The ODEQ Data Grade Matrix doesn't provide a standard method for grading ORP accuracy and precision. ORP drift up to 25 mV is very common in portable units, and holding the unit in the sample water for >30 seconds is considered a reliable method for sampling ORP (Suslow, 2004). Since ORP is highly variable in a system, ORP measurements should be considered just a glance at the parameter rather than a fixed point (Suslow, 2004). The YSI 6920 V2 Multi-Parameter Manual states that the accuracy of the ORP probe is determined if the post-sampling audit value is within the 221 to 241 mV range. For the purposes of this study, the accuracy of the ORP is considered normal if the previous statement was true, and the precision of ORP is considered normal if there is less than 25 mV difference between the two sample points, and will be flagged otherwise.

**QA/QC Results**

All data accuracy was graded at a B or higher, and was almost always an A or A+. All ORP post-sample checks were within 221 to 241 mV. The sonde is therefore considered to have performed accurately throughout the duration of the study.

Data precision was a bit more complicated. The total number of water quality samples taken was 100. Most data was graded at a B or higher (mostly an A+), but turbidity was lower than a B nine times, dissolved oxygen was lower than a B nine times, and ORP drifted more than 25 mV twice. For turbidity, five of these nine times the turbidity was under 20 NTU. The criteria for getting a B in this case is ±1 NTU (as opposed to <30% difference if higher than 20 NTU), so
the sample replicates could be only a couple NTU different and it wouldn’t
receive a B grade. For our purposes, it is acceptable to know the general
turbidity, since in general the pools are extremely turbid (usually between 500
and 1,200 NTUs), and well-fed sources such as guzzlers are typically much
lower. Knowing that the turbidity is approximately 20 NTU or less is still very
useful for our study. For dissolved oxygen, five of the nine times the data was
graded E, meaning the replicates were within 1 and 2 mg L\(^{-1}\) different, and the
remaining four were greater than 2 mg L\(^{-1}\) different (a C grade is worse than an E
grade in this case). Additionally, samples were casually taken and not according
to this procedure the very first day of sampling, including not taking replicates
(07Jul2011; four samples taken total). The data is still considered valuable and
will be flagged.

The two data values recorded are averaged for reporting purposes, which
reduces any in field precision error. When the data grade fell below a B, the data
is flagged.
### Data Validation Criteria for Water Quality Parameters Measured in the Field

<table>
<thead>
<tr>
<th>Quality Level</th>
<th>Quality Assurance Plan</th>
<th>Water Temperature Methods</th>
<th>pH Methods</th>
<th>Dissolved Oxygen Methods</th>
<th>Turbidity Methods</th>
<th>Conductivity Methods</th>
<th>Bacteria Methods</th>
<th>Data Uses</th>
</tr>
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<td>A+</td>
<td>DEQ QAPP approved by DEQ QA Officer</td>
<td>Thermometer Accuracy checked with NIST standards</td>
<td>A ± 0.5°C</td>
<td>pH electrode calibrated</td>
<td>Winkele pH titration or calibrated</td>
<td>Nephelometric Turbidity meter</td>
<td>Meter with temperature correction to 25°C</td>
<td>DEQ Approved Methods</td>
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<td></td>
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<td></td>
<td>± 0.5°C</td>
<td></td>
<td>Oxygen meter</td>
<td>A ± 0.2 mg/L</td>
<td>A ± 10%</td>
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<td></td>
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<td></td>
<td>A ± 0.3 mg/L</td>
<td>A ± 5%</td>
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<td></td>
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<td>A ± 0.2 mg/L</td>
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<td>A ± 10%</td>
<td>A ± 5% Standard value</td>
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<td>A ± 0.3 mg/L</td>
<td>A ± 5%</td>
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<td>Minimum Data Acceptance Criteria Met</td>
<td>Thermometer Accuracy checked with NIST standards</td>
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<td>Any Method</td>
<td>Winkele pH titration or calibrated</td>
<td>Nephelometric Turbidity meter</td>
<td>Meter with temperature correction to 25°C</td>
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<td>A ± 0.5 S.U.</td>
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<td></td>
<td>A ± 1 mg/L</td>
<td>A ± 5%</td>
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<td>C</td>
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<td>A &gt; ± 1.0°C</td>
<td>A &gt; ± 0.5 S.U.</td>
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<td>Nephelometric Turbidity meter</td>
<td>Meter with temperature correction to 25°C</td>
<td>DEQ Approved Methods</td>
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<td>A &gt; ± 2 mg/L</td>
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**Figure 43. Data Quality Grading Matrix**
5.3. Appendix 3 – Temporal Variability of Water Quality Parameters
Figure 44. Temporal Variation of Temperature.
Figure 45. Temporal Variation of Specific Conductivity.
Figure 46. Temporal Variation of pH.
Figure 47. Temporal Variation of Oxidation/Reduction Potential.
Figure 48. Temporal Variation of Turbidity.
Figure 49. Temporal Variation of Dissolved Oxygen.
Figure 50. Temporal Variation of Nitrate.
Figure 51. Temporal Variation of Chloride.
Figure 52. Temporal Variation of Bromide.
Figure 53. Temporal Variation of Sulfate.
Figure 54. Temporal Variation of Fluoride.
Figure 55. Temporal Variation of Phosphate.
5.4. Appendix 4 – Water Quality Data Tables

Table 8. Dugouts Outside of Basins Data

<table>
<thead>
<tr>
<th>Dugouts Outside of Basins</th>
<th>Average</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Standard Deviation</th>
<th>Error</th>
<th>Difference between average and median</th>
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<td>6.96</td>
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<td>0.45</td>
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<td>pH</td>
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<td>8.40</td>
<td>7.13</td>
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<td>497.23</td>
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<td>ODO%</td>
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<td>426.1</td>
<td>116.68</td>
<td>24.88</td>
<td>41.70</td>
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<tr>
<td>Dugouts Inside Basins</td>
<td>Average</td>
<td>Median</td>
<td>Min</td>
<td>Max</td>
<td>Standard Deviation</td>
<td>Error</td>
<td>Difference between average and median</td>
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</tr>
<tr>
<td>ODO_Conc_mg/L</td>
<td>7.69</td>
<td>7.17</td>
<td>0.29</td>
<td>14.59</td>
<td>2.71</td>
<td>0.51</td>
<td>0.52</td>
</tr>
<tr>
<td>Resistivity_KOhm.cm</td>
<td>6.01</td>
<td>5.23</td>
<td>0.76</td>
<td>19.19</td>
<td>4.54</td>
<td>0.86</td>
<td>0.78</td>
</tr>
<tr>
<td>Salinity_ppt</td>
<td>0.18</td>
<td>0.12</td>
<td>0.03</td>
<td>0.71</td>
<td>0.17</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>TDS_g/L</td>
<td>0.23</td>
<td>0.16</td>
<td>0.04</td>
<td>0.92</td>
<td>0.22</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Chloride_ppm</td>
<td>16.58</td>
<td>4.94</td>
<td>0.16</td>
<td>274.23</td>
<td>51.01</td>
<td>9.64</td>
<td>11.64</td>
</tr>
<tr>
<td>Bromide_ppm</td>
<td>0.11</td>
<td>0.03</td>
<td>0.00</td>
<td>1.13</td>
<td>0.23</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Sulfate_ppm</td>
<td>2.70</td>
<td>0.95</td>
<td>0.01</td>
<td>25.75</td>
<td>5.20</td>
<td>0.98</td>
<td>1.76</td>
</tr>
<tr>
<td>Fluoride_ppm</td>
<td>0.38</td>
<td>0.17</td>
<td>0.02</td>
<td>3.29</td>
<td>0.63</td>
<td>0.12</td>
<td>0.21</td>
</tr>
<tr>
<td>Nitrate_ppm</td>
<td>1.22</td>
<td>0.01</td>
<td>0.00</td>
<td>18.30</td>
<td>3.75</td>
<td>0.71</td>
<td>1.21</td>
</tr>
<tr>
<td>Phosphate_ppm</td>
<td>2.60</td>
<td>1.99</td>
<td>0.00</td>
<td>12.00</td>
<td>2.83</td>
<td>0.53</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Table 14. Hart Mountain Cow Exclusion Data

<table>
<thead>
<tr>
<th>Cows Excluded</th>
<th>Average</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Standard Deviation</th>
<th>Error</th>
<th>Difference between average and median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp_C</td>
<td>21.63</td>
<td>21.19</td>
<td>15.70</td>
<td>29.25</td>
<td>3.13</td>
<td>0.63</td>
<td>0.45</td>
</tr>
<tr>
<td>SpCond_mS/cm</td>
<td>0.37</td>
<td>0.27</td>
<td>0.10</td>
<td>1.25</td>
<td>0.31</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td>pH</td>
<td>8.02</td>
<td>8.09</td>
<td>7.32</td>
<td>9.16</td>
<td>0.45</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>ORP_mV</td>
<td>109.37</td>
<td>108.00</td>
<td>30.50</td>
<td>168.50</td>
<td>29.00</td>
<td>5.80</td>
<td>1.36</td>
</tr>
<tr>
<td>Turbidity_NTU</td>
<td>574.20</td>
<td>539.60</td>
<td>4.40</td>
<td>1340</td>
<td>437.13</td>
<td>87.43</td>
<td>34.60</td>
</tr>
<tr>
<td>ODO%</td>
<td>84.67</td>
<td>81.75</td>
<td>46.90</td>
<td>119.90</td>
<td>15.48</td>
<td>3.10</td>
<td>2.92</td>
</tr>
<tr>
<td>Cond_mS/cm</td>
<td>0.35</td>
<td>0.26</td>
<td>0.09</td>
<td>1.14</td>
<td>0.29</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>ODO_Conc_mg/L</td>
<td>7.45</td>
<td>7.26</td>
<td>4.38</td>
<td>10.78</td>
<td>1.30</td>
<td>0.26</td>
<td>0.19</td>
</tr>
<tr>
<td>Resistivity_KOhm.cm</td>
<td>5.06</td>
<td>3.91</td>
<td>0.88</td>
<td>11.48</td>
<td>3.29</td>
<td>0.66</td>
<td>1.15</td>
</tr>
<tr>
<td>Salinity_ppm</td>
<td>0.18</td>
<td>0.13</td>
<td>0.05</td>
<td>0.62</td>
<td>0.15</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>TDS_g/L</td>
<td>0.24</td>
<td>0.17</td>
<td>0.06</td>
<td>0.81</td>
<td>0.20</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Chloride_ppm</td>
<td>6.41</td>
<td>3.29</td>
<td>0.25</td>
<td>25.76</td>
<td>6.44</td>
<td>1.29</td>
<td>3.12</td>
</tr>
<tr>
<td>Bromide_ppm</td>
<td>0.11</td>
<td>0.03</td>
<td>0.00</td>
<td>0.45</td>
<td>0.13</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td>Sulfate_ppm</td>
<td>5.24</td>
<td>3.38</td>
<td>0.05</td>
<td>25.75</td>
<td>6.83</td>
<td>1.37</td>
<td>1.86</td>
</tr>
<tr>
<td>Fluoride_ppm</td>
<td>0.37</td>
<td>0.25</td>
<td>0.04</td>
<td>1.10</td>
<td>0.34</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>Nitrate_ppm</td>
<td>0.26</td>
<td>0.04</td>
<td>0.00</td>
<td>2.10</td>
<td>0.53</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
<td>Phosphate_ppm</td>
<td>3.09</td>
<td>2.07</td>
<td>0.00</td>
<td>12.00</td>
<td>3.16</td>
<td>0.63</td>
<td>1.02</td>
</tr>
</tbody>
</table>
Table 15. Cows Inclusion Data

<table>
<thead>
<tr>
<th>Cows Included</th>
<th>Average</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Standard Deviation</th>
<th>Error</th>
<th>Difference between average and median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp_C</td>
<td>18.44</td>
<td>19.46</td>
<td>4.41</td>
<td>27.59</td>
<td>6.35</td>
<td>0.89</td>
<td>1.02</td>
</tr>
<tr>
<td>SpCond_mS/cm</td>
<td>0.59</td>
<td>0.32</td>
<td>0.06</td>
<td>4.65</td>
<td>0.75</td>
<td>0.10</td>
<td>0.27</td>
</tr>
<tr>
<td>pH</td>
<td>8.42</td>
<td>8.42</td>
<td>6.91</td>
<td>10.24</td>
<td>0.81</td>
<td>0.11</td>
<td>0.00</td>
</tr>
<tr>
<td>ORP_mV</td>
<td>99.03</td>
<td>113.00</td>
<td>-223.50</td>
<td>222.00</td>
<td>75.81</td>
<td>10.62</td>
<td>13.97</td>
</tr>
<tr>
<td>Turbidity_NTU</td>
<td>632.33</td>
<td>664.95</td>
<td>0.55</td>
<td>1295</td>
<td>470.43</td>
<td>65.87</td>
<td>32.62</td>
</tr>
<tr>
<td>ODO%</td>
<td>102.93</td>
<td>84.45</td>
<td>3.20</td>
<td>426.05</td>
<td>85.13</td>
<td>11.92</td>
<td>18.48</td>
</tr>
<tr>
<td>Cond_mS/cm</td>
<td>0.55</td>
<td>0.26</td>
<td>0.05</td>
<td>4.55</td>
<td>0.74</td>
<td>0.10</td>
<td>0.29</td>
</tr>
<tr>
<td>ODO_Conc_mg/L</td>
<td>9.52</td>
<td>7.75</td>
<td>0.29</td>
<td>33.57</td>
<td>6.99</td>
<td>0.98</td>
<td>1.77</td>
</tr>
<tr>
<td>Resistivity_KOhm_cm</td>
<td>4.50</td>
<td>3.86</td>
<td>0.22</td>
<td>19.19</td>
<td>3.93</td>
<td>0.55</td>
<td>0.64</td>
</tr>
<tr>
<td>Salinity_ppt</td>
<td>0.30</td>
<td>0.15</td>
<td>0.03</td>
<td>2.49</td>
<td>0.39</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>TDS_g/L</td>
<td>0.39</td>
<td>0.21</td>
<td>0.04</td>
<td>3.02</td>
<td>0.48</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>Chloride_ppm</td>
<td>18.50</td>
<td>6.78</td>
<td>0.00</td>
<td>274.23</td>
<td>41.45</td>
<td>5.80</td>
<td>11.72</td>
</tr>
<tr>
<td>Bromide_ppm</td>
<td>0.13</td>
<td>0.04</td>
<td>0.00</td>
<td>1.13</td>
<td>0.25</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Sulfate_ppm</td>
<td>5.82</td>
<td>1.20</td>
<td>0.01</td>
<td>113.00</td>
<td>16.98</td>
<td>2.38</td>
<td>4.62</td>
</tr>
<tr>
<td>Fluoride_ppm</td>
<td>0.44</td>
<td>0.22</td>
<td>0.02</td>
<td>3.29</td>
<td>0.62</td>
<td>0.09</td>
<td>0.22</td>
</tr>
<tr>
<td>Nitrate_ppm</td>
<td>0.76</td>
<td>0.02</td>
<td>0.00</td>
<td>18.30</td>
<td>2.84</td>
<td>0.40</td>
<td>0.74</td>
</tr>
<tr>
<td>Phosphate_ppm</td>
<td>3.03</td>
<td>1.18</td>
<td>0.00</td>
<td>21.70</td>
<td>4.59</td>
<td>0.64</td>
<td>1.85</td>
</tr>
</tbody>
</table>
5.5. Appendix 5 – Python Code for Vernal Pool Water Surface Area Extraction

```python
# Derives Water Surface Polygons from Image Rasters and Computes Surface Area Change Through Time
#
# This code performs maximum likelihood classification on a set of raster bands for two multispectral SPOT images, and clips them to the same
# extent for proper temporal change analysis. It then converts the classified water surfaces to polygons, then calculates the area of the
# polygons. The water surface areas are then accessed from the attribute tables in the created shapefiles. Since this code works equally well
# for SPOT 4 and SPOT 5 data, the spatial resolution of the SPOT 5 data is lessened to match SPOT 4 for appropriate temporal analysis. Statistics
# are then run on the surface area of water in each image. It also computes the overall percent change in the total surface area water over the
# two time points.
#
# Inputs:
# Although designed for and tested on SPOT 4 and 5 multispectral images, any raster image file with multiple bands should work. Additional
# input is a reflectance signature file (.gsg), based on the image reflectances, and a polygon feature class consisting of a single polygon
# of the spatial range to be analyzed, both created by the user.
#
# Outputs:
# This code outputs the Maximum Likelihood Classification raster, the Raster to Polygon raster,
# the Calculated Areas raster, prints the resulting polygon areas and related statistics to debug, and to a .csv file.
#
# IMPORTANT NOTES:
# 1) The image files being compared must be over the same spatial extent for the end statistical comparisons to be significant.
# 2) The Arc Spatial Analyst Extension, Numpy and Scipy must be installed on the running computer for it to work.
# 3) The image and .gsg reflectance files must be present under the environment workspace designated.
# 4) Search and replace all "Date1" and "Date2" with two dates of images.
# 5) Search and replace all "Clipper" with the spatial range polygon feature class appropriate for clipping images.
#
# By: Sara Wyland
# Date: May, 2013
```

try:
    # Import system modules
    import arcpy
    from arcpy import env
    from arcpy.sa import *
    import numpy
    from scipy import stats

    # Allows us to run the script repeatedly without deleting the intermediate files, so you don't have to keep renaming the output file.
    arcpy.env.overwriteOutput=True

    # Set environment settings
    env.workspace = "c:/Users/Sara/Desktop/SPOT_Unalt"

    # Set local variables in first 4 lines; insert the two raster file names to analyze for water, and the two .gsg spectral files.
    # Note: It is recommended to create a new signature (.gsg) file for each image run, for best quality of the resulting polygons.
    inRaster1 = " .TIF"
    inRaster2 = " .TIF"
    sigFile1 = "c:/Users/Sara/Desktop/SPOT_Sig_Files/.gsg"
    sigFile2 = "c:/Users/Sara/Desktop/SPOT_Sig_Files/.gsg"
    probThreshold = "0.0"
    aPrioriWeight = "EQUAL"
    aPrioriFile = ""
    cutConfidence1 = "c:/Users/Sara/Desktop/SPOT_Proc/MaxConfidence1"
    cutConfidence2 = "c:/Users/Sara/Desktop/SPOT_Proc/MaxConfidence2"

    # Check out the ArcGIS Spatial Analyst extension license
    arcpy.CheckOutExtension("Spatial")
arcpy.env.extent = arcpy.gp.extent

# Execute

"Clip" (by Extract by Mask) images so problematic SPOT borders dissapear, and any other regions not wanting to analyze.
print "Starting Clip"

# Execute ExtractByMask
outExtractByMask1 = ExtractByMask(inRaster1, "c:/Users/Sara/Desktop/SPOT_Clip_Polys/Polys.gdb/Clip_Polys/Clipper")
outExtractByMask2 = ExtractByMask(inRaster2, "c:/Users/Sara/Desktop/SPOT_Clip_Polys/Polys.gdb/Clip_Polys/Clipper")

# Save the output
outExtractByMask1.save("c:/Users/Sara/Desktop/SPOT_Prc/ClipDate1")
outExtractByMask2.save("c:/Users/Sara/Desktop/SPOT_Prc/ClipDate2")
print "Clip Done"

# Execute Maximum Likelihood Classification
mlcOut1 = MLClassify("c:/Users/Sara/Desktop/SPOT_Prc/ClipDate1", sigFile1, probThreshold, aPrioriWeight, aPrioriFile, outConfidence1)
mlcOut2 = MLClassify("c:/Users/Sara/Desktop/SPOT_Prc/ClipDate2", sigFile2, probThreshold, aPrioriWeight, aPrioriFile, outConfidence2)

# Save the output
mlcOut1.save("c:/Users/Sara/Desktop/SPOT_Prc/MxCDate1")
mlcOut2.save("c:/Users/Sara/Desktop/SPOT_Prc/MxCDate2")
print "Maximum Likelihood Classification done"

# Convert the classified rasters to polygon shapefiles
arcpy.RasterToPolygon_conversion("c:/Users/Sara/Desktop/SPOT_Prc/MxCDate1","c:/Users/Sara/Desktop/SPOT_Prc/RtcPolyDate1.shp","SIMP","VALUE")
arcpy.RasterToPolygon_conversion("c:/Users/Sara/Desktop/SPOT_Prc/MxCDate2","c:/Users/Sara/Desktop/SPOT_Prc/RtcPolyDate2.shp","SIMP","VALUE")
print "Raster to Polygon done"
# Calculate Areas - Calculates the areas of the created polygons (i.e., surface areas) and writes them to the attributes table for each polygon
arcpy.CalculateAreas_stats("c:/Users/Sara/Desktop/SPOT_Proc/RtoPolyDate1.shp","c:/Users/Sara/Desktop/SPOT_Proc/AreasDate1.shp")
arcpy.CalculateAreas_stats("c:/Users/Sara/Desktop/SPOT_Proc/RtoPolyDate2.shp","c:/Users/Sara/Desktop/SPOT_Proc/AreasDate2.shp")
print "Calculate Areas done"

# Select from using SQL statement to exclude the huge polygon of non-water and all SPOT 5 images less than 255 m^2 to make them comparable to SPOT 4):
arcpy.Select_analysis("C:/Users/SPOT_Proc/AreasDate1.shp","C:/Users/SPOT_Proc/AreasDate1_Fin.shp",""F_AREA" < 50000000 AND "F_AREA" > 255.0")
arcpy.Select_analysis("C:/Users/SPOT_Proc/AreasDate2.shp","C:/Users/SPOT_Proc/AreasDate2_Fin.shp",""F_AREA" < 50000000 AND "F_AREA" > 255.0")
print "Large and small polygons removed"

TheShapefile1="c:/Users/Sara/Desktop/SPOT_Proc/AreasDate1_Fin.shp"  # Want to set the shapefile to the first parameter
TheShapefile2="c:/Users/Sara/Desktop/SPOT_Proc/AreasDate2_Fin.shp"
ThePoolArea="F_Area"  # Defines the attribute column to access. This is column shows the surface area of the vernal pools.
TheRow1=arcpy.SearchCursor(TheShapefile1)  # This is where you can define the specific set of rows in an attribute table.
TheRow2=arcpy.SearchCursor(TheShapefile2)
print "check"

PoolSurfaceAreas1=[]
PoolSurfaceAreas2=[]

# Loop the attribute value through all of the column's rows, and print to a list:
for TheR in TheRow1:
    TheSAValue=TheR.getValue(ThePoolArea)
    SAValue=round(TheSAValue)
    PoolSurfaceAreas1.append(SAValue1)
print("The Pool Surface Areas list 1: "+str(PoolSurfaceAreas1))
# Loop the attribute value for the second set of water polygons:
for TheRow in TheRows2:
    TheSAValue2=TheRow.getValue(ThePoolArea) |
    SAValue2=round(TheSAValue2)
    PoolSurfaceAreas2.append(SAValue2)
print("The Pool Surface Areas list 2: "+format(PoolSurfaceAreas2))

# The following statistics compares the vernal pool water surface areas at the two time points and shows some changes in water levels:
MinimumSAValue2=numpy.min(PoolSurfaceAreas2)
print ("The Date2 Surface Area Minimum Value ="+format(MinimumSAValue2))

MinimumSAValue1=numpy.min(PoolSurfaceAreas1)
print ("The Date1 Surface Area Minimum Value ="+format(MinimumSAValue1))

MaximumSAValue2=numpy.max(PoolSurfaceAreas2)
print ("The Date2 Surface Area Maximum Value ="+format(MaximumSAValue2))

MaximumSAValue1=numpy.max(PoolSurfaceAreas1)
print ("The Date1 Surface Area Maximum Value ="+format(MaximumSAValue1))

SAStandardDeviation2=numpy.std(PoolSurfaceAreas2)
print ("The Date2 Surface Area Standard Deviation ="+format(SAStandardDeviation2))

SAStandardDeviation1=numpy.std(PoolSurfaceAreas1)
print ("The Date1 Surface Area Standard Deviation ="+format(SAStandardDeviation1))

SAAverage2=numpy.average(PoolSurfaceAreas2)
print ("The Date2 Surface Area Average ="+format(SAAverage2))
SAAverage1 = numpy.average(PoolSurfaceAreas1)
print ("The Date1 Surface Area Average =" + format(SAAverage1))

SAMedian2 = numpy.median(PoolSurfaceAreas2)
print ("The Date2 Surface Area Median =" + format(SAMedian2))

SAMedian1 = numpy.median(PoolSurfaceAreas1)
print ("The Date1 Surface Area Median =" + format(SAMedian1))

SATotal2 = numpy.sum(PoolSurfaceAreas2)
print ("The Date2 Total Surface Water Area =" + format(SATotal2))

SATotal1 = numpy.sum(PoolSurfaceAreas1)
print ("The Date1 Total Surface Water Area =" + format(SATotal1))

PercentChange = ((SATotal2 - SATotal1) / SATotal2) * 100
print ("Percent Change =" + format(PercentChange) + ")")

# Create a .csv file and print the results to it:
TheFile = open("c:/Users/Sara/Desktop/SPOTProc/VP_Water_Date1_Date2.csv", "w")
TheFile.write("0, 1, 2, 3") # Header Column, edit as necessary
TheFile.write("\n") # Carriage Return

TheFormat = "{0}, {1}, {2}, {3}" # Tells the following how to put the variables in relation to each other

# This tells it to write this in TheFormat outlined above.
TheFile.write(TheFormat.format("Total Water Surface Area in m^2", SATotal2, SATotal1, PercentChange))
TheFile.write("\n")
TheFile.write(TheFormat.format("Minimum Surface Area in m^2", MinimumSAValue2, MinimumSAValue1, ""))
TheFile.write("\n")

TheFile.write(TheFormat.format("Maximum Surface Area in m^2", MaximumSAValue2, MaximumSAValue1, ""))
TheFile.write("\n")

TheFile.write(TheFormat.format("Average Surface Area in m^2", SAAverage2, SAAverage1, ""))
TheFile.write("\n")

TheFile.write(TheFormat.format("Median Surface Area in m^2", SAMedian2, SAMedian1, ""))
TheFile.write("\n")

TheFile.write(TheFormat.format("Surface Area Standard Deviation in m^2", SAStandardDeviation2, SAStandardDeviation1, ""))
TheFile.write("\n")

TheFile.close()

    print "done"

except:
    print("An error occurred")
    print arcpy.GetMessages()
5.6. **Appendix 6 – Appendices Bibliography**

