Western Toad (*Anaxyrus boreas*) Distribution in the Chehalis Basin: Maxent Modeling for Conservation

by

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ABSTRACT

Western Toad (*Anaxyrus boreas*) Distribution in the Chehalis Basin: Maxent Modeling for Conservation

Isabella Nadia Timmons

The decline in amphibian biodiversity is a major concern on a global scale; Western toads (*Anaxyrus boreas*) reflect this problem locally within Washington State. Decline of Western toad has been attributed to habitat loss and fragmentation. Loss of suitable habitat is currently a concern with an implementation of a proposed dam to the Chehalis River located in Western Washington. Washington Fish and Wildlife has been conducting Western toad encounter surveys since 2014 to document distribution of the Western toad. Western toad has been known to breed exclusively within the mainstem Chehalis for reasons unclear. Breeding habitat and oviposition occurrence has been observed within the Chehalis river basin. The landscape factors associated with these occurrences have not been examined use data on Western toad distribution in the Chehalis Basin to develop a better understanding about its overall breeding distribution using an ecological niche model termed *MaxEnt*. Specifically, I look at four climate variables and three land cover layers to better understand landscape-scale factors and how they may influence Western toad breeding. Out of the seven variables, the factor with the most influence on occurrence of Western toad was precipitation. This research may be the foundation of future analysis with *MaxEnt* modelling to further understand how certain variables may limit the distribution of Western toad and other amphibians. Furthermore, the models produced in this research may inform conservation or restoration efforts if a dam is realized in the future.

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Introduction:

Decline in amphibian biodiversity is a major concern for conservation biologists globally; Western toad (*Anaxyrus boreas*) reflect this problem locally. Western toads have been declining and with continued fragmentation and loss of habitat, they may be lost along with other aquatic fauna who also use those habitats without intervention (Blaustein, A.R., & Wake, D.B., 1995; Blaustein, A.R., & Kiesecker, J.M., 2002; Davis, T.M., & Gregory, P.T., 2003; Fisher R.N., & Shaffer, H.B., 1996). The Western toad is a species of concern for biologists due to its decline in range. In Washington State, it is currently a state candidate for formal listing that is slated for review. Washington State Department of Transportation (DOT) proposed a dam to the Chehalis River mainstem that poses a potential threat to the regional success and persistence of Western toad. The overarching purpose of the proposed dam to the Chehalis mainstem, is to protect infrastructure, homes, and the integrity of towns along the river that have historically experienced devastating floods. However, the proposed dam may alter suitable toad breeding and rearing habitat and may alter the Chehalis system making it less biodiverse and ecologically degraded.

The Chehalis system is unique in western Washington. Western toads breed in the Chehalis Basin in portions of the Chehalis mainstem and its major tributaries (Hayes, Tyson, Douville, & Vadas, 2018). In particular, breeding habitat has been identified but the limits of what constitutes suitable breeding habitat has not be determined, especially at a basin-scale. Further, the footprint of the proposed dam overlies some of the densest Western toad oviposition sites (Hayes, Tyson, Douville, & Vadas, 2018). Western toad is under consideration due to its designation as a target species, a species that must have special attention under the Chehalis River Aquatic Species Restoration Plan (ASRP) according to Washington State Fish & Wildlife. Western toad is a species of concern within Washington State. Focus on understanding local populations has been on the radar of both state departments of Fish & Wildlife and National Parks within Washington because of their overall decline.

The ASRP is a restoration plan that specifically considers Western toad because of the potential decline or loss of presence that may occur in the future. The ASRP has goals to protect and restore habitat processes and ecological health in the Chehalis Basin because of ecological degradation. The Chehalis Basin Strategy, an organization funded by the State of Washington, has a purpose of using adaptive management techniques to reduce flood damage and restore aquatic species habitat. The ASRP was developed by the Chehalis Basin Strategy and is focused on restoration goals and projects. One of the ASRP's goals is to restore aquatic species habitat.

This research will provide useful insight into Western toad breeding distribution within the Chehalis and will be foundational for future studies and restoration/conservation projects. I will use data on Western toad distribution in the Chehalis Basin to develop habitat suitability maps for the entire Chehalis Basin using a species distribution model (SDM) termed MaxEnt. This information is basic knowledge needed to develop an understanding of how the proposed dam in the Chehalis River mainstem headwaters might affect the Western toad populations in the basin. By studying current distribution of Western toad, researchers can further their understanding of limiting factors that influence Western toad breeding and oviposition behavior due to landscape-scale factors.

Western toad are aquatic and terrestrial animals who rely on suitable stream, wetlands, and forests to complete their life cycle. One of the most critical life stages, which is also when individual toads are most vulnerable, is during oviposition or tadpole rearing (Biek, Funk, Maxell, & Mills, 2002). Western toads typically breed in shallow ponds, or slow to still-moving water, and areas with little canopy cover (Hayes, Tyson, Douville, & Vadas, 2018). During the time after oviposition, egg strings are susceptible to numerous dangers. Some of the risks include predation, disease, poor water quality/contaminated water, and even desiccation of breeding ponds. These dangers not only affect egg strings but can threaten recently developed eggs such as larvae. This research will focus on the landscape-level characteristics and environmental factors that influence breeding distribution of the Western toad. Landscape-level characteristics have not been defined in depth previously, this research aims to fill gaps in our knowledge on Western toad breeding.

Species-specific information on distribution is imperative to make responsible natural resource management decisions, especially if conservation of a specific species is the main goal. This information is typically hard to obtain due to resources necessary to track populations, especially at a large scale. Knowing the distribution within a local landscape will be imperative to protecting the Western toad in Washington State. This project will identify breeding distribution within the Chehalis Basin located in western Washington utilizing maximum entropy modeling, also known as *MaxEnt*. *MaxEnt* generates probability distribution and will fundamentally aid in our understanding of the environmental factors that influence habitat preference for oviposition. Loss of critical habitat is suspected to occur with the implementation of a flood control dam to the Chehalis River. Loss of Western toad to the Chehalis Basin can reflect a future trend within Washington state, as critical wetlands and riverine habitat is further transformed and affected by anthropogenic influence.

Much of Western toad breeding is not well understood. Gaps in our knowledge of suitable breeding habitat will limit the ability to effectively conserve habitat for this species. The research question that fundamentally guides this research is: *What are the landscape-level characteristics* *and environmental factors that influence the breeding distribution of the Western toad along the Chehalis river mainstem and its tributaries?*

To answer this question, I will first conduct a literature review where I discuss natural history, conservation status, known breeding behavior, and current threats. I will also give background into the field of species distribution modeling and explain pros and cons of *MaxEnt*, essentially justifying my choice. Second, I will discuss methodology and show maps of the study area with points of occurrence. These points will be combined with the environmental and climatic variable layers to be analyzed through *MaxEnt*. Third, I will analyze the results derived from *MaxEnt* and discuss future implications. *MaxEnt* outputs will include a current distribution of toad breeding activity within the basin, from that I can critically analyze model performance. I will conclude with a discussion about *MaxEnt* outputs and further interpret the results while making real world connections specifically in regard to a dam implementation.

Literature Review

Introduction:

Amphibian decline and biodiversity loss has been a concern for conservation biologists around the world. Western toad (*Anaxyrus boreas*) is a species with a fairly large geographic range in North America. However, Western toad has been declining in recent years. Literature has attributed the decline to habitat loss, competition of invasive species, and even disease outbreak; such as Chytridiomycosis. There are many threats to amphibians on a global scale, locally Western toads face the impacts of habitat loss. Amphibians are losing critical habitat such as wetlands, aquatic streams, and terrestrial habitat surrounding marshy areas.

I will further discuss the challenges Western toads face, but before that I will give an overview of the natural history of Western toad. To begin this literature review of Western toad, I will explain the geographic range of occupation, taxonomical naming, and physical characteristics. After that, I will describe breeding activity and explain why Western toad is considered an "explosive breeder." The next topic I include in this literature review, is telemetry tracking of toads which naturally leads to toad movement and the impressive distances toads travel. I then explain reasons for toad decline and the many challenges toads face in an ever-changing urban world, as well as the conservation status on a federal versus local scale and why Western toad is under consideration in the ASRP. I will finish this chapter with information about species distribution models and other machine learning techniques to better justify my choice of using *MaxEnt* application in this project.

Natural History

Boreal Toads: Species description

Western toad *Anaxyrus boreas* was formerly known as *Bufo boreas,* and is within the family of Bufonidae. *Anaxyrus boreas* was previously included in the genus *Bufo* (used in past literature from before 2006). In literature, it is common to find *Bufo boreas* used instead of *Anaxyrus boreas* due to the relatively recent name change. The genus change was following the work of Frost et al., during 2006, which reflects the restriction of *Bufo* to the Eastern Hemisphere (2006). Bufonidae is a diverse amphibian family and is the only family in anurans that contain all toad members. Anaxyrus is the genus that Western toad falls in, and these toads are endemic to North America and Central America. Related toads are; *Anaxyrus boreas halophilus, Anaxyrus californicus, Anaxyrus woodhowsii, Anaxyrus canorus,* and *Anaxyrus exsul.* Western toad occurs throughout western North America, ranging from southern Alaska to Baja California. Ranges continue eastward within the Rocky Mountains into Colorado, Montana, Utah, and Wyoming (Figure 1.) (Weidmer & Hodge, 1996; Ross et al., 1995; Hammerson, 1999).

Anaxyrus boreas is broken down into subspecies, two of the most common subspecies found in north America are *Anaxyrus boreas boreas*, and *Anaxyrus boreas halophilus*. *A. b. boreas* is found from the east slopes of Rocky Mountains to the Pacific Ocean. *A. b. halophilus* occurs on the west coast as well, but in more southern regions such as northern California to Baja California. This research includes information on the species as a whole even though the subspecies in Washington is the *A. b. boreas*. Drastic differences in the morphological variation between the subspecies have not been observed (Hewitt, 1996), some DNA research has been done to start distinguishing the differences between subspecies to reflect how diverse this species may be (Goebel, Ranker, Corn &Olmsted, 2009). Conserving subspecies and smaller groups may be a way to better manage conservation projects since Western toad occupies a fairly large range.

Western toad can be found throughout mountainous areas, ranging in sea level elevation to around 11,000 ft—few amphibians are found at alpine elevations such as these (Burger & Bragg, 1947; Carey, 1993). The name *Anaxyrus boreas* has Greek origins meaning (*Anaxyrus*) king or chief, and (*boreas*) meaning northern or northwind. Western toads are found within the state of Washington and are predominantly present west of the Cascade Mountains (Figure 2).

Figure 1*. Range of Western toad (Adopted from IUCN SSC Amphibian Specialist Group 2015. Anaxyrus boreas. The IUCN Red List of Threatened Species 2015: e.T3179A53947725. accessed on 08 April 2019).*

Western toad is a large robust toad with dry warty skin. Adults usually have a singular cream-colored strip that runs down their dorsal/back. Body coloration can vary, but is commonly green, tannish rust, dusky gray, or yellowish brown. They have distinct oval paratoid glands, which is the distinguishing characteristic between True Toads (Bufonidae) from other frogs.

There are no cranial crests present on Western toads' head and their pupils are horizontal. Both males and females have lighter coloration on the throats compared to the rest of the body. Adults range from about 5 to 13 cm (snout-vent length).

Females are usually larger than males due to the differences in energy requirements for reproduction. Female toads have been observed to travel further distances from natal ponds, attributed to emigration and locating of uninhabited habitat. Toads travel further distances from bodies of water than other amphibians due to the ability to retain moisture and the size of fat bodies in vitro (basically, the ability to store energy is possible because of their fat bodies). The ability for female toads to travel further distances than their male counterpart has been attributed to the presence of larger fat bodies.

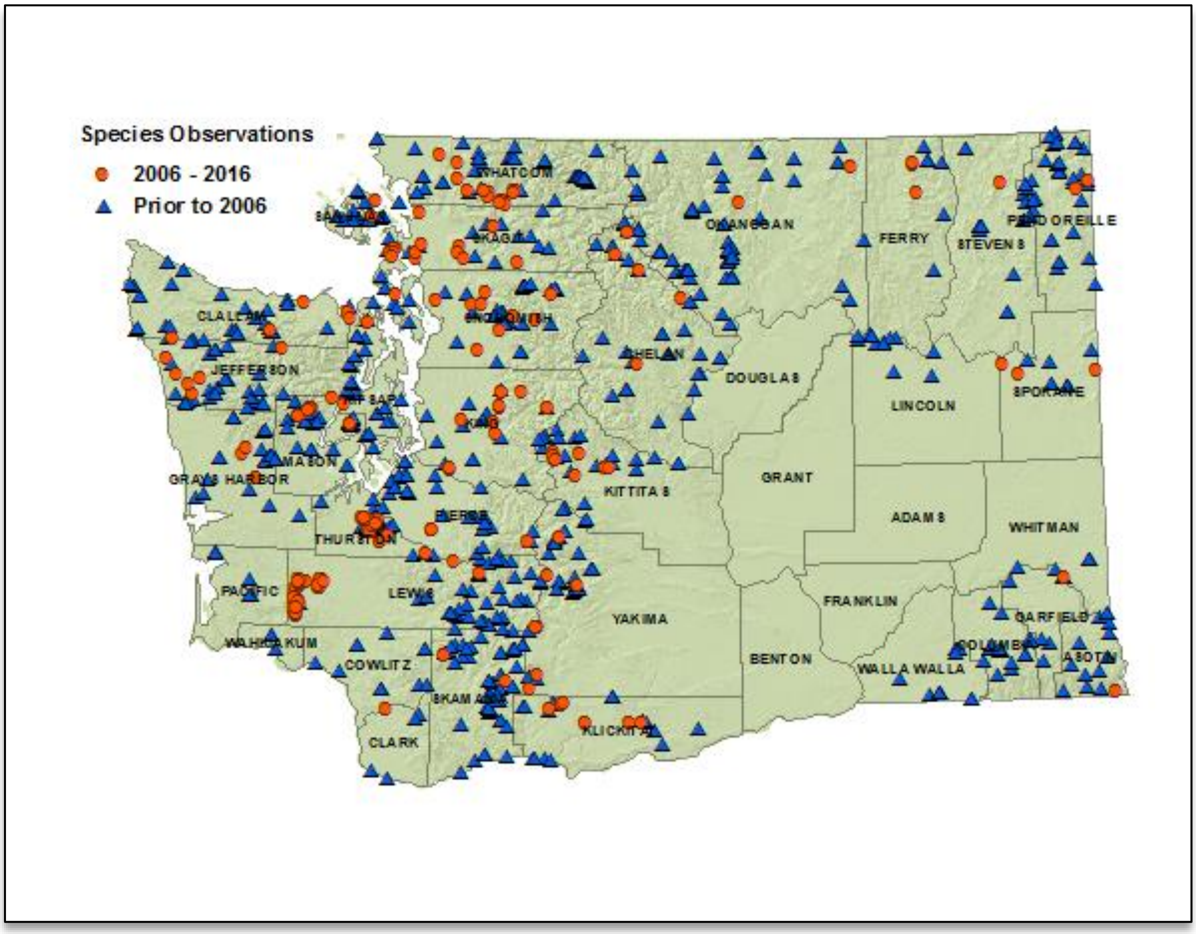

Figure 2. *Western toad observations in Washington State.Year 2006-2016 are depicted as red circles, and years prior to 2006 are represented as blue triangles (Adopted from Washington Herp Atlas, 2013)*

Breeding:

Breeding season varies depending on the climate, elevation, and breeding area availability. Breeding occurs early spring, depending on temperature and availability of melted ponds/wetlands. In Central Oregon, male Western toads reach sexual maturity by the age of 3 years, while females reach maturity at 4-5 years (Blaustein et al., 2001). Timing of breeding occurs from the range of late April to late June. Timing of breeding is dependent on elevation—lower elevation breeding occurs sooner than higher elevation populations due to breeding pond availability and increase in temperature. Breeding takes place in open, shallow, slow to nonmoving ponds. Breeding windows have been observed in Central Oregon to be as short as 2-3 weeks (Olson, Blaustein, O'Hara, 1986). Western toads are considered "explosive" breeders due to this short window of which breeding occurs.

Toads return to breeding locations year after year and lay eggs in the form of a gelatinous string which can contain thousands of individual larvae. Development of egg strings to metamorphosis is about 40-45 days after oviposition (Biek, Funk, Maxell, & Mills, 2002). The rate of metamorphosis has been observed to be at a faster rate with an increase in temperature and a slight decrease in breeding depth (Blaustein et al., 2001). Eggs strings are laid around 12 cm deep and are usually no shallower than 6 cm, egg strings laid in shallow water are at risk of predation via birds and other small mammals. During breeding season, it is most typical to find male toads closer to breeding ponds and females further away (Bartelt et al., 2004). Male toads attract females with chirping noses during the daylight hours and have been found to be active at breeding ponds at night (Blaustein et al., 1995).

For the most part, this species has been predominantly studied during breeding season and in aquatic environments. Studying Western toad during oviposition and during the breeding season is due to access and availability of toads. During the post breeding period, the Western toad begins to invest time and energy in finding suitable hibernation sites and have been found to hibernate communally (Browne & Paszkowski, 2010). Toads use refugia to avoid predation and desiccation, because of this locating toad can pose as a challenge and can be extremely difficult. Studies have indicated that after oviposition they become increasingly more terrestrial (Bull, 2006; Bartelt et al., 2004; Browne, Paskowski 2010). Tracking of toads on terrestrial landscapes is most effectively done with radio telemetry devices.

Telemetry Tracking:

Telemetry radiotracking is a popular way for researches to track movement of fairly mobile amphibians such as Western toad. Without telemetry tracking of Western toad, we would not fully understand their true occupied range. The power that telemetry tracking offers biologists and ecologist is a measurement of the distance an individual can travel during a set period (day, month, season). Without knowing accurately how far toads travel in terrestrial landscapes conservation/protection of wetland and riparian zones may fall short. In fact, current buffers surrounding aquatic habitat does not reflect distances toads travel seasonally.

Unfortunately, current recommendations in the literature do not protect terrestrial amphibian habitat to the extent that is required by the Western toad. Goates, Hatch, and Eggett (2007) argued, that current standards for aquatic buffer zones are inadequate protection for species in riparian and wetland systems (2007). Western toad utilizes both riparian and wetland habitat substantially during the breeding period. During the post-breeding period toads utilize substantially more terrestrial habitat. A commonly used buffer of 30.5 m for aquatic areas is ineffective for protecting all critical habitat for boreal toads. (Lee, Smyth, Boutin, 2004; Goates, Hatch, & Eggett, 2007). Boreal toads move much further than the recommended 30.5 m during major life stages such as post-breeding.

During breeding season toads tend to stay close to natal ponds specifically for the reason to put energy in mating. Telemetry tracking was used to observe movement during breeding and post-breeding periods in Targhee National Forest in southeastern Idaho. About 60% of tracked toads were observed to be within 200 m of natal ponds during the breeding season (Figure 3) (Bartelt, Peterson, Klaver, 2004). The same study found that during the post-breeding season toads traveled distances of up to 6,230 m (Barlet, Peterson, Klaver, 2004). Bartelt and researchers (2004), also observed distances traveled to be different dependent on sex. Female toads traveled significantly further than male counter parts; 6,230 m compared to 3,870 m (2004). Research has shown during the post-breeding period female toads typically travel further distances than males. Muths (2003) observed sexual differences in average distance traveled post-breeding, females traveled about 721.46 m, this is about three times greater than the distances traveled for male toads (Muths, 2003). Toads may travel further distances without tracking devices on them, the numbers observed with telemetry tracking may be underrepresenting the true movement of toads.

Boreal Toad Movement:

Western toads are dynamic animals who utilize both aquatic and terrestrial habitat. They are able to travel fairly large distances on land due to the ability to retain moisture and water. Other amphibians usually have a much smaller terrestrial range due to limited water access. Western toad has the capability to travel lengthy distances in terrestrial environments which leads to patchy distributions. Small patch dynamics leave populations facing threats of extirpation and even local extinction and may even cause bottlenecking within the small populations.

In a study conducted in northeastern Oregon, radio-telemetry devices were attached to toads via waistbands for recording toad movement (Bull, 2006). Tracking of individual toads led researchers to better understand sexual differences in movement. During the post-breeding period, toads spend about 81% of time in terrestrial habitat and 19% in aquatic environments that were not categorized as breeding sites (Bull, 2006). This indicates that toads spend the majority of post-breeding time in terrestrial landscapes. Often times these terrestrial landscapes lack protection because commonly used aquatic buffers do not encompass these distances (Goates, Hatch, & Eggett, 2007). Further, this has led researchers to believe that breeding sites are utilized primarily for oviposition, and terrestrial habitat is essential core habitat for other important life history functions.

Because toads move in both terrestrial and aquatic environments, corridors aid to facilitate dispersal. Toads are fairly slow-moving amphibians and slow reaction time leave them vulnerable to predators. Toads walk rather than jump. However, Western toads produce toxins that are secreted via skin glands that many predators avoid. In the terrestrial landscape, toads take advantage of the ability to maintain body moisture and water retention, to travel distances of up to 2,000 m for female toads in a single day (Bull, 2006). Females travel longer distances than male counterparts due to the larger size and capacity to store and carry water in the lymph sacs and bladder. Sexual differences in movement has been attributed to the different energy requirements of adult toads between the sexes (Bartelt et al., 2004; Morton & Pereyra, 2010). Bartelt, Klaver, and Porter (2010) also found that movement of western toad were greater in females than males.

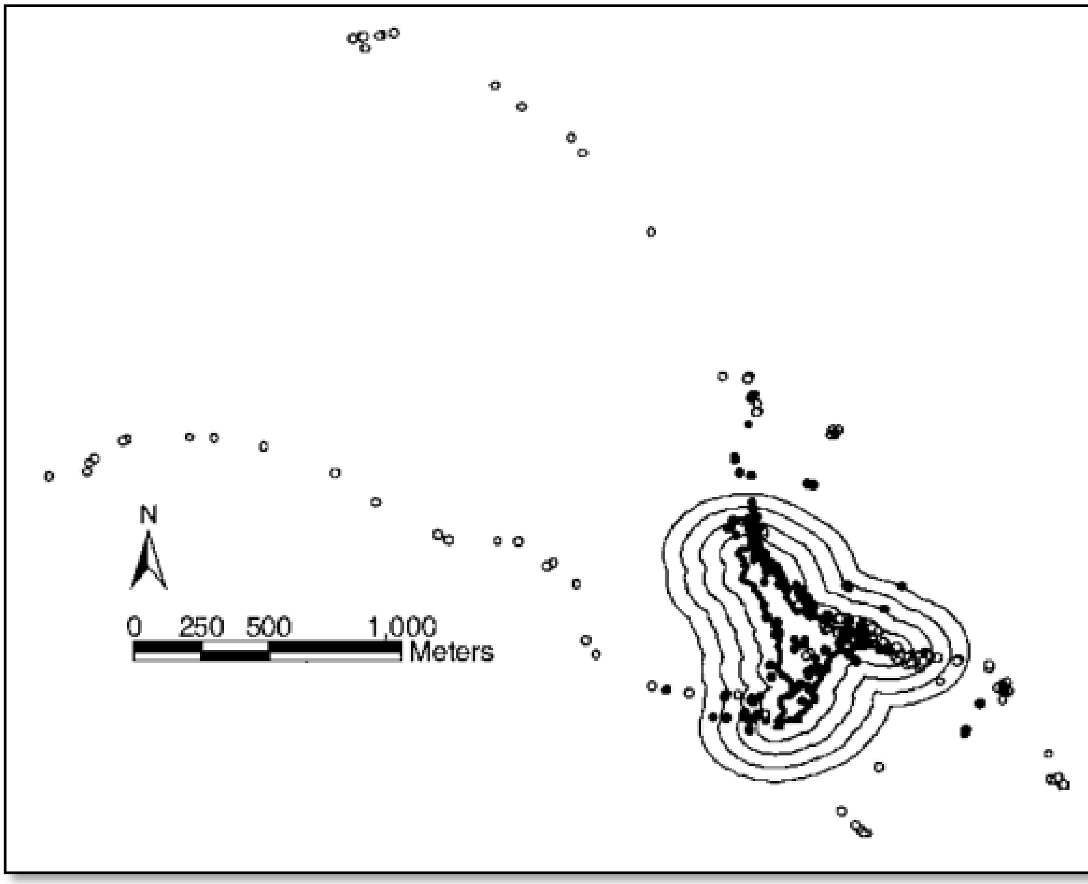

***Figure 3**. Proximity of toads to breeding ponds.Western toad distribution around breeding pond. Females represented as open circles; males represented with filled circles. 50-meter buffer increments represented around breeding pond polygon. Adopted from Bartelt, P. E., Peterson, C. R., & Klaver, R. W. (2004). Sexual differences in the post-breeding movements and habitats selected by western toads (Bufo boreas) in southeastern Idaho. Herpetologica, 60(4), 455-467.*

Bartelt and researchers, used Niche Mapper--an ecological niche model--and found that female toads traveled further distances, subsequently reflecting stronger habitat selection than male toads (Bartelt, Klaver, & Porter, 2010).

Toads utilize instream movement as a dispersal method significantly more than previously realized. In a study done in western Montana, researchers found Western toads swam up and down streams as part of their home range (Adams et al., 2005). Home range is the area a species occupies to complete normal life activities, this is associated with realized distribution (Burt, 1943). A species home range depends on seasonal variation (such as hibernation, migration etc.). In Montana, toads were found to travel instream distances up to 500 m in a single day during mid-summer (Adams et al., 2005). More research is needed to fully understand how much Western toad uses streams as a mode of transportation. Future studies of Western toad movement may serve as beneficial information.

Current and Future Threats

Conservation Status:

Western toads are a candidate species in Washington, Oregon, and Idaho. Candidate species are named by US Fish and Wildlife Service (FWS). Candidate species can be plants and animals that have information on their biological status and threat. Candidate species are usually trending towards endangered or threatened under the endangered species act (ESA). Western toad, according to IUCN is a species of least concern even though they have been declining in range and are a species that has experienced local extinction due to fragmentation of populations (IUCN, 2015). The Western toad is under consideration for WDFW scientists due to its designation as a target species, a species that must have special consideration under the Chehalis River Aquatic Species Restoration Plan (ASRP). The ASRP was formed by the State of Washington, Quinault Indian Nation, the Confederated Tribes of the Chehalis and other stakeholders. The ASRP was developed to create a comprehensive strategy to restore the ecological health of the Chehalis River Basin. This includes the protection of habitats, ecosystem processes, and populations of aquatic and semi-aquatic species. The ASRP not only has goals of protection and restoration of natural systems, but also aims to create flood and climate-resilient systems that will eventually support humans that depend on their success. Persistence of Western toad may be negatively affected when a dam is realized in the Chehalis River because of hydrological impacts.

Urbanization: Implications on Toad Movement

With the growing human population and increased way of urban living, many areas have been changed drastically. As development encroaches on wetlands and further infrastructure is introduced, Western toad not only face threats of habitat fragmentation, but also increased risk of mortality due to automobiles via road development (Riley et al., 2005; Adams, 2002). According to Davis (2002), roads are particularly damaging because they subdivide continuous habitat, disrupt metapopulation dynamics, and are a source of considerably direct mortality by motor vehicles (2002). Urban roads are also indirectly affecting stream hydrology and the surrounding stream habitat, causing a deep disruption in both aquatic and terrestrial environments (Deguise & Richardson, 2009).

Not all roads are created equal. Roads can be broken down to forest, urban, rural, and highway/freeway systems. Different road types consequently have varying degrees of the facilitation or hindrance of movement by boreal toads. For example, the impact of urban roads is much more devastating to boreal toad populations compared to much less frequented forest roads. This can be attributed due to the heavy usage, motor fatality of toads, and through increased exposure to toxic chemicals from automobiles. Urban roads are travelled more frequently and are typically made up of impervious material which leads to the increased production of surface run-off affecting hydrology, sediment disposition, and even altercation of habitat structure along stream beds (Riley et al., 2005).

Conservation efforts to minimize road mortality of Western toads can be quite extensive and unrealistic. Davis (2002) recommended avoidance of building around breeding sites, and to implement road closure around migratory paths of the Western toad. This is intended to mitigate the hazards roads pose (Davis, 2002). Even though road closures are seldom possible, there is the option of "toad tunnels" that are built underneath roads (Adams, 2002). Toad tunnels are intended to facilitate migration of amphibian and other small vertebrates in avoidance with the hazards of traffic. These efforts are still in the works and the success rates are not completely known.

Forest Development: Forest Roads

As mentioned above, roads come in many different sizes and range in the impact they can have on an ecosystem. Forest roads have a lot less traffic compared to urban road systems and may serve as movement corridors for Western toad. Movement patterns were found to be high on logging roads, suggesting that forest roads in fact, facilitate the movement and potentially optimize connectivity between fragmented forests (Deguise & Richardson, 2009). It is also worthy to note, that logging roads themselves are not necessarily being used for movement but the adjacent culverts (2009). Distinguishing the difference between urban and forest roads will aid in clearly indicating hazards for conservation purposes. Forest roads are much less of a threat to Western toads compared to urban road systems; this relationship should be investigated further.

Climate Change:

Climate changes can have varying levels of consequence. Some organisms are better suited to adapt to climate changes; however, some species are sensitive and are especially vulnerable. This is true for the Western toad and other amphibians. Figure 4 Illustrates some of the themes of climate changes and how they may affect amphibian in direct and indirect ways.

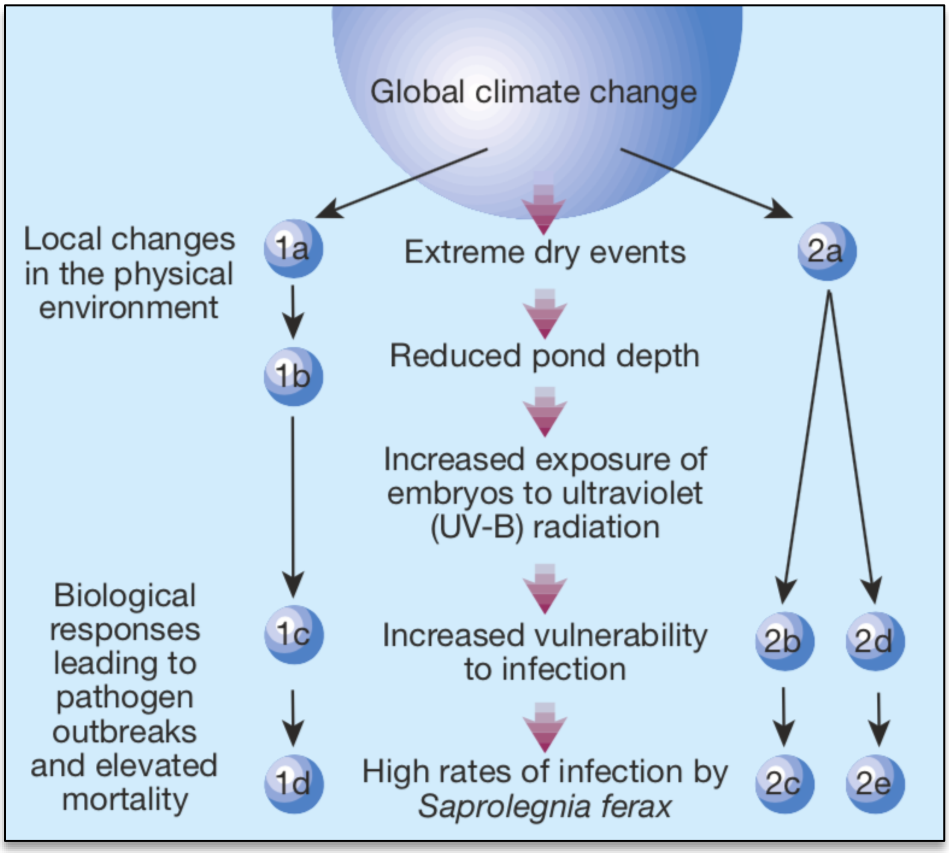

Figure 4. *Influence of climate change on amphibian populations. Direct and indirect effects of climate changes. Adopted from Pounds, J. A. (2001). Climate and amphibian declines. Nature, 410(6829), 639.*

Breeding patterns of Western toad and other amphibians may be influenced by warming temperatures, less precipitation, and earlier snowmelt. Effects on breeding activities due to climate changes may be reflected in population declines (Blaustein et al., 2001). Increase in temperature can lead to earlier breeding in some anuran populations however, there has been observations indicating a slight trend associated between warmer temperatures and earlier breeding season behavior of Western toad (Blaustein et al., 2001). Temperature can be less of a determining factor in the timing of breeding compared to water availability. Reduction in water depth at oviposition sites may lead to an increased mortality rate of amphibian embryos due to synergistic effects between ultraviolet-B radiation and pathogenic fungus (Kieseker & Blaustein, 1995). Because many amphibians lay in standing water, eggs and larvae are particularly vulnerable to desiccation and UV-B radiations. Desiccation of breeding habitat is heavily influenced on precipitation and availability to permanent water sources rather than temperature. With the increase in temperature and overall less precipitation due to climate change, anticipation can be assumed that standing pools may become desiccated before egg and larvae develop (Blaustein et al., 2001). Many climate-induced changes that negatively impact amphibians act synergistically. Pathogenic outbreaks in amphibian populations are linked to change of UV-B exposure, this is especially a concern for amphibians found at higher elevation like the Western toad (Kiesecker, Blaustein, & Belden, 2001).

Amphibian Chytrid Fungus:

Chytridiomycosis is the amphibian disease caused by one of many chytrid fungus that has been the catalyst for amphibian population decline and even extinction. The amphibian chytrid, also known as frog chytrid, is formally known as *Batrachytrium dendrobatidis* (Bd). Bd is an interesting fungus because of its devastating effect on amphibian populations. Once Bd infects amphibians, those species develop the disease and may experience reddened/discolored skin, abnormal skin shedding, seizures, and abnormal activity levels. Bd occurs inside the cells of the outer layer of skin, it then causes hyperplasia and hyperkeratosis which essentially leads to thickening of the skin. This is especially dangerous to amphibian species because of the way they use their skin for respiration and absorption of water and electrolytes through their skin. Amphibians that are at the post-metamorphic stage of development are more susceptible to suffering from adverse effects of Bd, due to their keratin-rich skin. Tadpoles lack the development of keratinized skin and are less likely to be affected (De Leòn, Vredenburg, & Piovia-Scott, 2017).

Chytridiomycosis may reduce the survival of wild boreal toads by 31-41% (Pilliod et al., 2010). Exposure dosage of Bd zoospores and the duration of exposure play an important role in the length of survival by *Anaxyrus boreas* according to Carey et al. (2006). Carey and researchers (2006) found a significant correlation between the number of days survived following the exposure of Bd zoospores and body mass of toads ($r = 0.795$, $n=30$, $P<0.00001$) (2006). Certain amphibian species have been observed to have an increased sensitivity or vulnerability to Bd, this is not well understood but Bd resistance has been attributed to symbiotic fungi on some amphibian's skin (Ellison et al., 2014).

Although Bd can be present on many amphibian hosts, not all amphibians are susceptible to Bd. In a laboratory experiment, researchers found that American bullfrogs were resistant to one of the tested Bd strains but susceptible to the other (Gervasi et al., 2013). This research included two strains of Bd. Results support the hypothesis that some amphibian species (bullfrogs) may persist with infection of Bd and can be carriers of disease to less tolerant species (Gervasi et al., 2013). Western toad is not a "Bd resistant" amphibian and is particularly vulnerable to Bd outbreaks. In an experiment conducted by Blaustein et al., Western toad larvae were observed to have an increased mortality rate when exposed to *B. dendrobatidis*, compared to other species such as; cascade frog *Rana cascadae,* bull frog *Lithobates catesbeianus*, and pacific tree frog *Psuedacris regilla*) (Blausteinet al., 2005). Care should be taken to avoid Bd exposure in known areas of Western toad populations.

The Chehalis River: Implications of a Dam

The Chehalis River is the most diverse basin in western Washington, which reflects the fact that it is the only basin in western Washington that reaches into three ecoregions (Figure 5) (the Cascades, the Olympics, and Willapa Hills) - for example, it has the highest diversity of native amphibians of any area in Washington State.

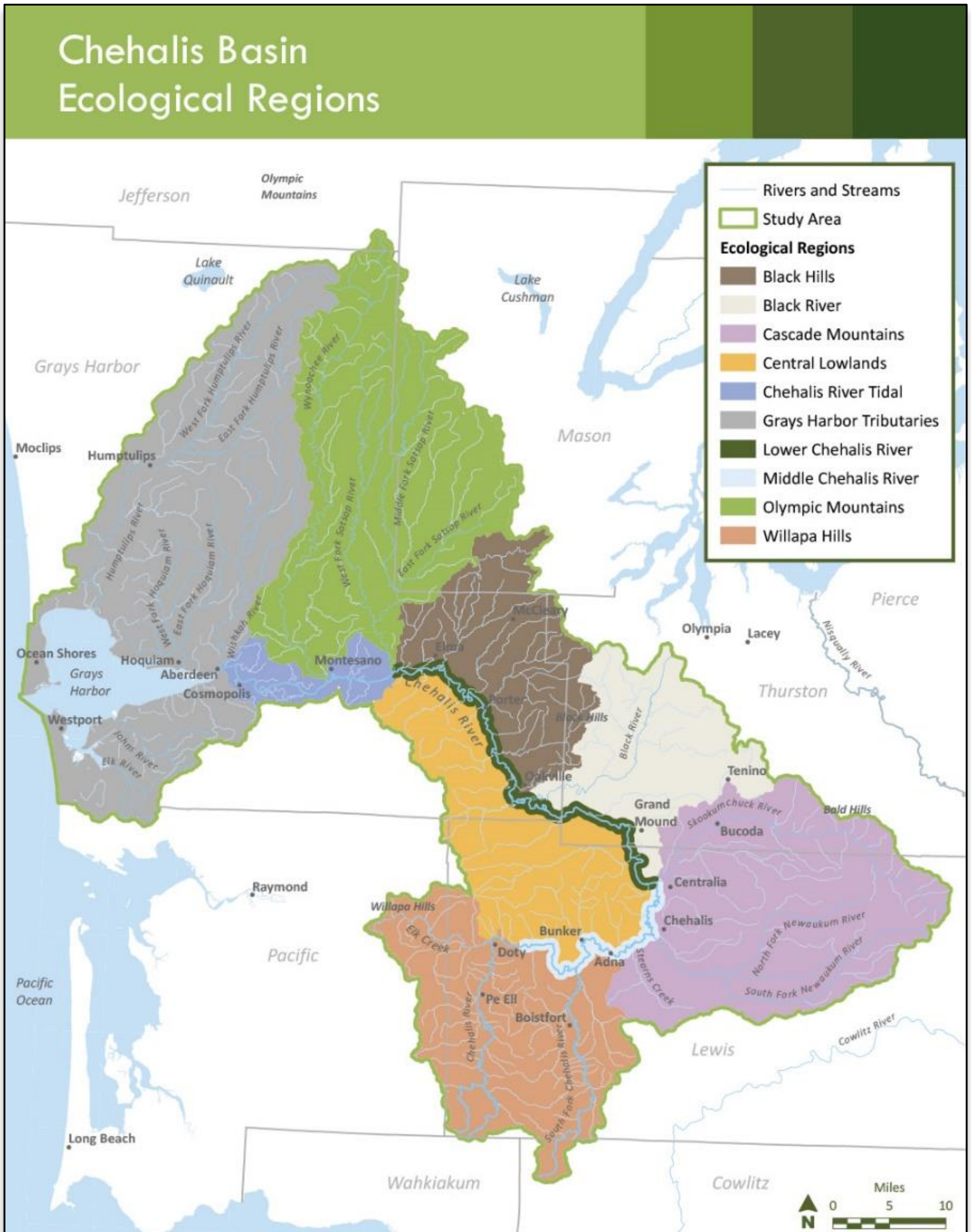

***Figure 5**. The Chehalis Basin.*

However, its highly fertile floodplain is also among the most important agricultural areas in Washington State. Land use patterns in the basin, including those that address flood reduction, may conflict with maintaining its natural diversity. Flood damage reduction is a key aspect of the Chehalis Basin Strategy. As previously mentioned, the Chehalis system is unique in that the portions where Western toad breed, almost exclusively oviposition occurs instream situations in portions of the Chehalis mainstem and its tributaries (Hayes, Tyson, Douville, & Vadas, 2018).

The Chehalis River is broken down into several distinct ecoregions (Figure 5). The image illustrates the connectivity of the Chehalis river and its far-reaching capacity within western Washington. There is about 23 million dollars in state funding to local projects throughout the Chehalis Basin to reduce flood damage and restore habitat (Office of Chehalis Basin). To reduce flood damage in the Chehalis basin, Flood Control Zone District is proposing to construct a new flood retention facility and temporary reservoir near the Lewis county town of Pe Ell (Chehalis Basin Strategy).

One of the important elements that make up the Chehalis Basin's natural biodiversity is the Western toad. Amphibians serve as excellent water quality indicators because of their sensitivity. Western toads are also an important part of the Chehalis Basin ecosystem and are valuable in ways that are not easily distinguished, such as they serve as valuable food sources for other small animals. If flood control efforts in the Chehalis Basin further degrade its habitat or threaten its populations, risk of extirpation may be increased. Changes of habitat due to the flood reduction project may alter suitability of habitat and may impact breeding distribution within the basin.

Proposed dam options for the headwaters of the Chehalis River mainstem pose several possible issues for the Western toad. First, positioning the dam and reservoir may eliminate habitat for seasonal activities. We can assume this will happen because breeding has been observed to occur within the proposed dam's footprint (Hayes, Tyson, Douville, & Vadas, 2018). Second, modification of flows in the mainstem Chehalis River may alter habitat downstream if, and when, Western toads use that habitat seasonally. Third, the position of a dam and reservoir has the potential to fragment Western toad habitat in a way that either alters their seasonal movements or disconnects exchange within the local population (increasing risk of genetic bottlenecking), altering its probability of extirpation.

Habitat utilized during the Western toad's life cycle is not completely understood. Different phases of Western toad life cycle require certain habitat that environmental factors influence. In particular, gaps in our understanding exist in the landscape factors that limit Western toad use of aquatic and terrestrial habitats, especially during perhaps the most critical stage: oviposition. My project will focus on which landscape-scale factors limit oviposition habitat. This will be useful information for both the restoration projects under the ASRP, and the mitigation actions expected for losses if the dam construction project is realized. The ASRP and mitigation projects both address the focal elements of the Chehalis Basin Strategy, the ASRP, and flood reduction alternatives. Clearly illustrating why Western toads breed in certain portions of the Chehalis Basin will better equip future conservation and restoration projects for Western toad. Results that would achieve mapping the suitability of habitat would aid in management decisions. Habitat suitability maps can be the output of certain species distribution models such as a *MaxEnt* analysis.

Machine Learning and Species Distribution Modeling:

Within the last 25 years, the demand for species distribution models has increased in the field of conservation biology and ecology. This can be attributed to the need for accurate quantification of species-environment relationships, especially within changing environments. According to Guisan and Zimmermann (2000), "the quantification of such species-environment relationships represents the core of predictive geographical modeling in ecology" (2000). This type of quantification will only become more popular within the field of ecology due to its predictive capabilities especially in areas that are changing due to anthropogenic influence.

Computer modeling of species distribution involves statistical techniques and are driven by powerful machine learning systems. The foundation of machine learning is based on mathematical algorithms that essentially build models (with data termed as "training"), to produce outcomes in the form of predictions. The machine learning field includes many species distribution models (SDM) and ecological niche models (ENM). Each model involves differing approaches. This is most apparent in the input and output of the models, and the type of spatial analysis question they are intended to solve. SDMs are empirical models based loosely in ecology theory their output is of *habitat suitability maps* (Guisan & Thuiller, 2005). An SDM that is most applicable to this research is termed *MaxEnt*. In this portion of the paper, I will describe model building and model validation, explain why *MaxEnt* was chosen over other SDM techniques, and address limitations within the *MaxEnt* approach. Before this, I lead with some background of ENM and SDM analysis and what they offer.

Ecological Niche Modeling:

To address species distribution, ecologists use modeling methods such as ecological niche model (ENM) and species distribution model (SDM). Both are used to identify a species distribution across a landscape. The main difference between them is ENM estimates *potential distribution*, while SDM estimate *realized range*. The potential distribution is the geographic area where a species, without outside limitations such as competition or prey, would be able to utilize. This is different from realized distribution, which is the actual area occupied by the species. ENM, when used accordingly, have the ability to predict *potential distribution*, this is extremely useful for conservation. Niche-based models represent an approximation of species' ecological niche within a specific environment. These environments are made up with specific conditions (or constraints) that allow certain species' long-term survival. As an example, most toads have the ability to be further from moisture and water sources compared to a salamander. A particularly elegant ENM approach is maximum entropy model (*MaxEnt*). A key advantage of *MaxEnt* method is the ability to utilize presence-only data, rather than being dependent on presence-absence data. This is particularly useful when studying a species that can be challenging to locate or when only limited presence records are available (an endangered species, or historic records).

Maxent Analysis:

This project will use *MaxEnt* modeling to explore the relationship between species distribution and suitable habitat for the Western toad in the Chehalis River Basin. Using *MaxEnt*, I hope to gain better understanding of the constraints of Western toad distribution in the Chehalis Basin. That information is basic knowledge needed to develop an understanding of how the proposed dam in the Chehalis River mainstem headwaters might affect the Western toad populations locally. Before I get into methods, I describe *MaxEnt* and breakdown the process of *MaxEnt* analysis, using this project as an example.

MaxEnt method has a broad range in applicability and has been used for tracking many species, from marine mammals to invasive terrestrial plants (Edrin et al., 2010; Evangelista et al., 2008). *MaxEnt*, is a machine learning method that relies on simple and precise mathematical formulation to provide predictions of species distribution. This is calculated from a set of occurrence localities utilizing presence-only data. *MaxEnt* originated from statistical mechanics and has been further developed for ecology by Phillips. (Jaynes, 1957; Philips et al., 2006, Phillips et al., 2008, Phillips et al., 2011).

MaxEnt generates a probability distribution for habitat suitability across a study area allowing a comparison of suitability estimates among regions (Phillips S.J., Anderson R.P., & Schapire R.E., 2006). To examine the landscape-scale factors that limit Western toad breeding, I will use localities that will constitute oviposition occurrences taken by WDFW. These localities are GPS points of oviposition ($x_{1...}x_2$) within the Chehalis Basin, which will be the study area (L). I will compare environmental factors to identify the influence they have on oviposition.

The purpose of *MaxEnt* modeling technique, will be the ability to predict which areas within the Chehalis River satisfy the requirements of the Western toad's ecological niche, specifically relating to oviposition. Model performance will be evaluated by use of *Area under the curve* (AUC), a commonly used accuracy measure for ENM and other SDMs (Phillips S. J., & Dudík, M., 2008). ArcGIS will be used for mapping of distribution and analysis tools can provide helpful analysis of environmental variables (statistical tools). The total data will be partitioned into two groups: training and testing. Training data will be used to make the model, while the testing data is used for measuring the performance of the model. Model performance will be assessed with the area under a ROC curve (AUC). ROC is the omission and receiver operating characteristic analyses

MaxEnt relies on unbiased samples, the same is true for all species modeling. Small numbers of sample size can lead to misrepresented model distribution and should not be interpreted as predicting actual range (Blank and Blaustein, 2012). Typically, the bigger the sample size of locality points the better the model outputs will represent the species actual range.

Identifying regions characterized by similar environmental conditions to where the species occurs is what can still be achieved with small sample sets using *MaxEnt* methods (Pearson et al., 2007). It is important to note that, performance of most distribution models, including *MaxEnt*, decreases when the sample size is smaller <10n (Phillips, Dudík, 2008). Unfortunately, with endangered species low sample localities are usually all that is available (Wisz et al., 2008). The *MaxEnt* algorithm operates on a set of constraints, such as environmental factors, that describes what is known from the sample (training data set) distribution. *MaxEnt* predicts the probability distribution of the species across all the cells in the study area. To avoid overfitting, *MaxEnt* method employs maximum entropy principles and regularization parameters (Philips et al., 2006).

Why MaxEnt?

MaxEnt was deemed most applicable and appropriate for several reasons. Firstly, *MaxEnt* only requires presence records and utilizes presence background data to build the model. Presence-only data is stronger than presence-absence data due to the false-negatives that an absence can conclude. False-negatives can be attributed to the difficulty of detecting a species, which is especially an issue with amphibian surveys. I will further explain false-negatives in the determining presence section. By using *MaxEnt*, a modeling technique especially suited to process presence-only data, accurate predictions of habitat suitability can be achieved. Secondly, *MaxEnt* has the capability to use categorical environmental variables unlike other SDMs that are limited to continuous. Thirdly, *MaxEnt* is able to account for potential interaction between variables. Variable interaction and correlation can a cause model to lose predictive power, knowing any correlation between variables should be considered before model evaluation

(Phillips S.J. & Dudik M., 2008). Lastly, *MaxEnt* does not give equal weight to all variables, which is part of the machine learning algorithm to best fit a model with the data used. This is especially important to identify if certain variables are more important or influential within the model.

Model Building:

MaxEnt generates a probability distribution based on mathematical formulas using occurrence localities, background area, and covariates also known as environmental variables. *MaxEnt* is used alongside geographic information system (GIS) for geospatial analysis. *MaxEnt* is an open source software that is a stand-alone Java application (Phillips S.J., Dudik M., Schapire R.E., 2004). *MaxEnt* uses the background data points (at random) and outputs the distribution of covariates within the study area. The essential question *MaxEnt* answers is which pixels within a geographic region are occupied by the species and what is the probability of each pixel being occupied by said species. *MaxEnt* is rooted in maximum entropy principle and uses probability to address this lack of knowledge we have of species distribution. The inputs for model building are locality points in a CSV format. The geographic range is then established, and environmental variable layers are then combined with the locality points. The outcome is the index of suitability. *MaxEnt* outputs are maps that show the probability of suitable environmental conditions that are similar to the occurrence localities (Figure 6).

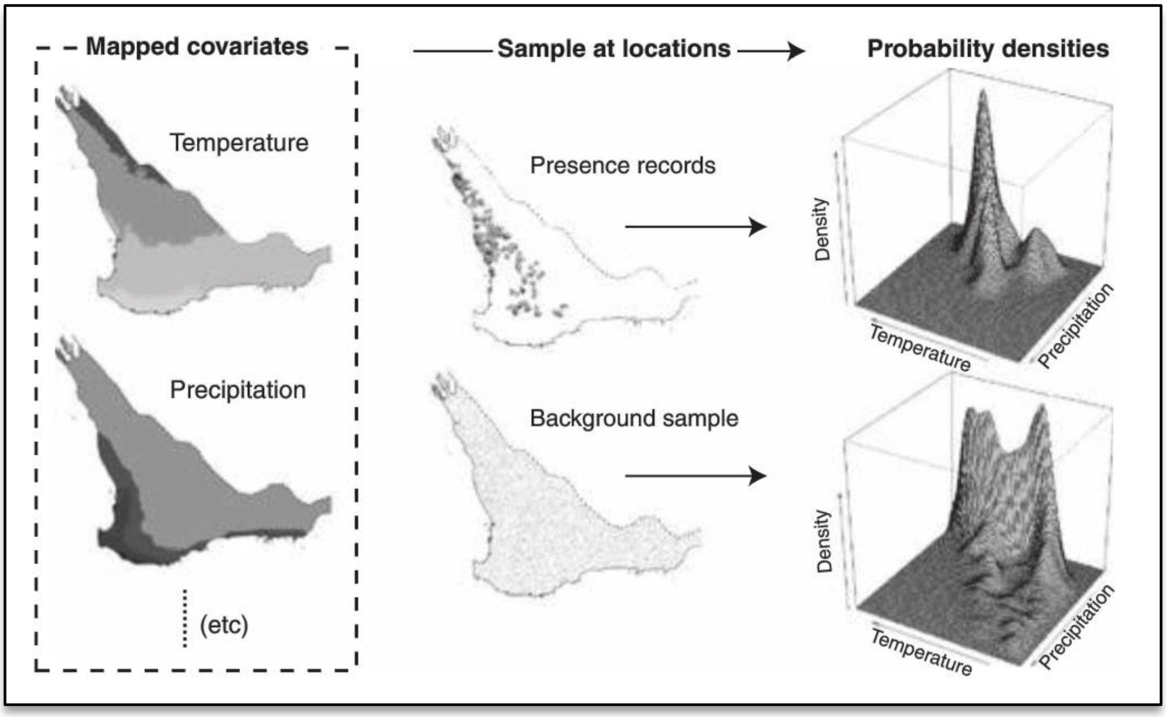

Figure 6. *Mapped covariates and probability densities.Individual covariate layers combined with both presence and background points to yield a MaxEnt prediction. Maps on the left, are covariates (temperature, precipitation, etc.). Maps in the center contain presence points and random background points used in MaxEnt modeling. Probability densities are the MaxEnt output. Adopted from A statistical explanation of MaxEnt for ecologist's p. 47, Elith J., Phillips S.J., Hastie T., Dudik M., Chee Y.E., & Yates C.J., 2011)*

Model Evaluation:

In the settings of *MaxEnt* there is the option to partition the data set of locality points into two groups. This data split is done for model evaluation. One group is dedicated to train the data while the second group is for model testing. Usually, the data gets split to about 70% for model training and 30% for testing. Testing of the model is conducted by the statistical analysis of the area under the receiver operating curve (ROC). This is also known as the AUC and is commonly used to assess model performance in distribution models. The value of the AUC ranges from zero to one. A powerful model, in the predictive sense, has a higher AUC value (closer to 1) and holds stronger statistical significance. It is important to note, that the AUC is not the probability of a presence of the species, but rather the suitability of the habitat to that species.

Conclusion:

The overarching purpose of the dam proposed to the Chehalis mainstem is to protect infrastructure, homes, and the integrity of towns along the river that have sustained historical flooding. The dam is a likely option due to the increase of flood damage to the town Pe Ell near Centralia, Washington. Western toad breeding habitat has been identified within the Chehalis mainstem but the limits of what constitutes suitable breeding habitat has not been determined, especially at a basin scale. Documenting breeding habitat and the limiting environmental factors will help biologists predicting the population-level effects of ecosystem changes. My research will fill the gap in knowledge of landscape-scale environmental factor limitations surrounding Western toad breeding. Defining the environmental variables that may influence suitability of habitat for breeding/rearing is a main goal of this project. This information will benefit restoration and mitigation efforts if a dam to the Chehalis is realized.

Methods

Study Area:

The study area is the Chehalis Basin located in western Washington State. The Chehalis basin is made up of 12 sub-watersheds. The Chehalis River is one of the most dynamic river basins in Washington state due to its high biodiversity and presence of native amphibian and fish species. Chehalis Basin is one of the largest basins in Washington State and drains over 2,660 miles^2, there are over 3,300 miles of rivers and streams within the basin. The Chehalis River flows into three distinct ecoregions, as an ecologically and geographically defined area, which includes the Olympic Mountains. Ecoregions reflect the ecological pattern that occurs on a particular landscape. Each ecoregion is distinctive from one another because of the complex plant and animal communities that make them up. The ecoregions that encompass the Chehalis Basin include: The Cascades, Puget Lowland, and Coastal Range. The Chehalis Basin is a treasure of western Washington and monitoring of this watershed has been conducted by the Washington Department of Fish and Wildlife (WDFW).

Washington Department of Fish & Wildlife has been conducting amphibian surveys in the Chehalis Basin to determine breeding distribution of Western toad in the Chehalis River mainstem and its tributaries since 2014 to date. Observation efforts that are included in this research occurred between 2014 and 2018. WDFW has been engaging in surveying and collecting basin-wide data on Western toad occurrence and breeding in the Chehalis Basin over the last 5 years and has records of Western toad from years prior. I will be using existing data through WDFW as the locality points. This project will be utilizing *MaxEnt* modeling to explore the relationship between species distribution and suitable habitat for the Western toad along the Chehalis River. The purpose of *MaxEnt* modeling technique, will be the ability to predict which areas within the Chehalis River satisfy the requirements of the Western toads' ecological niche, specifically relating to oviposition.

Determining Presence and Distribution

Monitoring Presence: VES

Visual encounter survey (VES) is a frequently used technique for collecting presence-only data of amphibian species. These surveys are typically done for long-term monitoring programs and can be accomplished with relatively few resources. However, VES are fairly time consuming and can lead to false-negatives because of the difficulty detecting amphibians. Nonetheless, they are widely used for obtaining amphibian presence and abundance across the world. Research has been conducted in Washington State that has compared two different survey techniques for abundance of stream associated amphibians (SAA) (Quinn et al., 2007). The techniques were rubble rousing versus light-touch. Rubble rousing is in-depth searching with or without nets setup downstream to capture SAA reality abundance (Wilkins & Peterson 2000). Light touch technique involves visually searching an area and overturning movable objects. Results indicated that the most ideal technique included low-false negative error rates, low variance, and cost effectiveness (Quinn et al., 2007). Rubble rousing took about 12 times as long than light-touch in application and had a higher abundance measure with an increased error rate (Quinn et al., 2007). Depending on time and resources available, certain survey methods may be a better option. VES, light touch, and rubble rousing can provide useful information and should be chosen depending on the degree to which researches are willing to accept false negative error rates. The data that was collected and used for this research was done via VES by WDFW. This means the actual distribution of Western toad may be larger than what is recorded.

Input data: Locality Data

Egg mass, tadpole, and adult pairs in amplexus were considered occurrence points for this research. GPS points were taken for locality points and a UTM was defined for all observations. All data that made up Dataset A was from surveys conducted during 2014-2018 field seasons. Dataset A contains all observed egg mass (EM) locations (all recorded as one locality), and tadpole clusters with individual number at 10,000 or more, combined with all points of adults in amplexus. Dataset A had 188 observation points. After sifting through data sources, I thought it would be beneficial to incorporate another locality dataset to see if more observations increased the model performance or decreased overfitting. This led to the creation of Dataset B, the dataset that would contain valuable breeding and rearing distribution that Dataset A lacked. To make Dataset B, I included all the points as in Dataset A. In addition, I included all larvae sighting (each sighting as one point) and did not exclude tadpole observations (Table 1). Dataset B also had years prior to 2014 included, this was because official Western toad surveys started in 2014 but other surveys prior to 2014 had Western toad observations. Because of the subtle differences between Dataset A and B, there is a subsequent difference in each model output. The main difference is that Dataset A represents the relative breeding distribution within the Chehalis Basin. Dataset B better represents breeding and tadpole rearing distribution. Keeping this in mind, outputs and results will indicate which is more compelling to answer the stated research question.

There are several aspects to mention about the observation data derived from WDFW. The locality points of egg strings were considered individual if at least three meters apart. This analysis does not focus on abundance, but it is important to note that all points were at least 3 meters apart. Because my research is focused on breeding and rearing habitat, there were a couple opportunities to decide what type of points to include. I chose to include observations of tadpoles and pairs in amplexus to optimize the dataset size and include sites that were used for oviposition and rearing. This is important to clarify that when optimizing the dataset the results infere distribution of toad breeding *and* rearing. I ran the model several times to show different model outputs with the use of different input data (the reason I include two datasets with monthly variation data). I considered tadpoles as part of both locality datasets due to the fact that larvae stay relatively close to their natal ponds due to risk of desiccation, predation, and lack of mobility. There is a difference in the number of tadpole (larval) observation points in Dataset A and B (Table 1).

Table 1. *Observation Points Included for Analysis*

Dataset	Years Included	Egg Mass	Tadpole	Pairs in amplexus	Total Observation
A	2014-2018	181	3	4	188
B	2013-2018	256	131	4	391

Including both data sets serves as an opportunity to compare and contrast projected habitat suitability maps of Western toad. Both deriving from WDFW data over the span of several years. Data set A includes points of egg mass locations with tadpoles that have not been developed enough to move freely within the water body (they remain proximate to the actual oviposition site) and adult pairs in amplexus. The tadpole observations were with numbers of 10,000 individuals (Figure 7). Data set B utilizes as many potential occurrence points as possible (Figure 8).

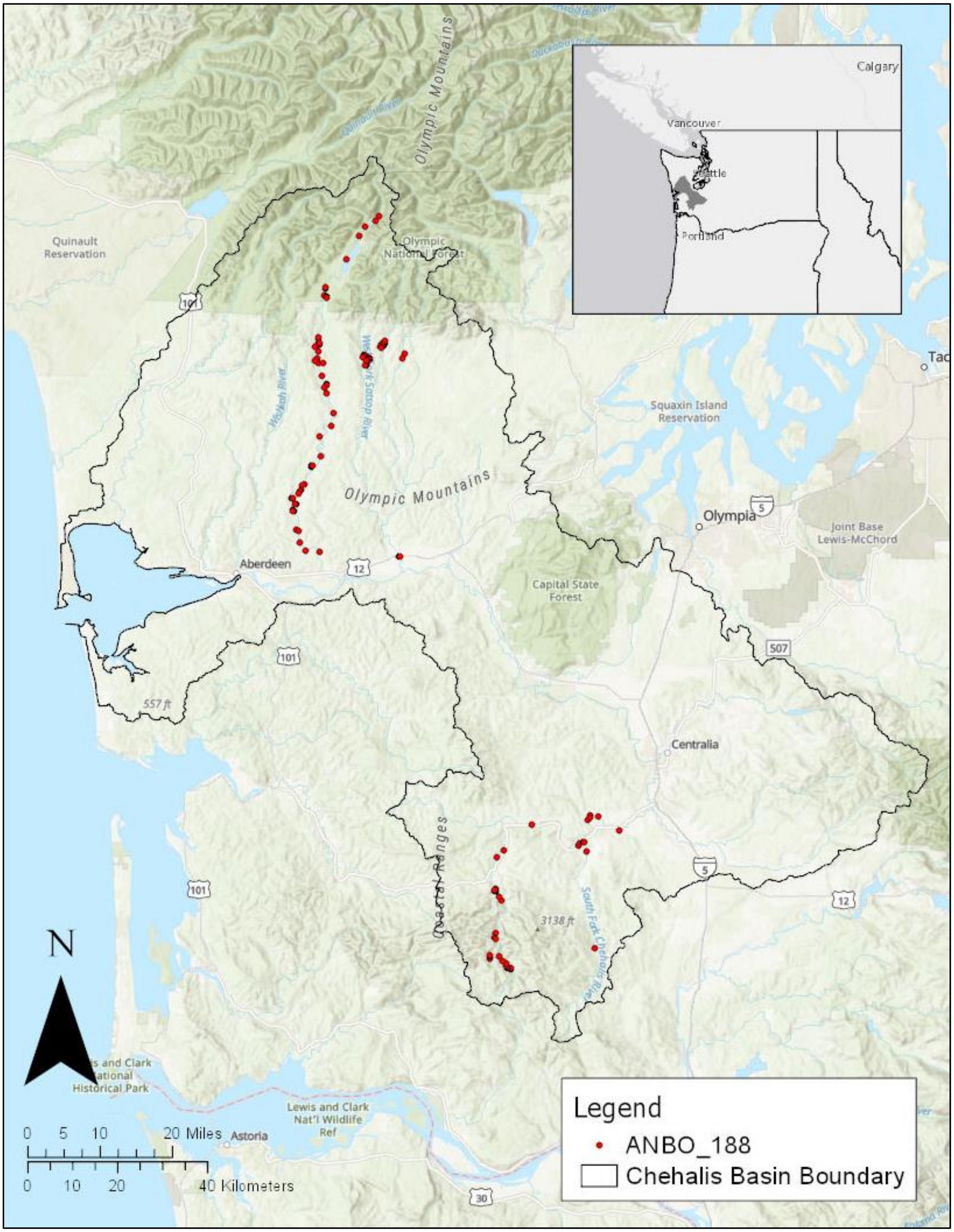

Figure 7. *Study Area with Data Set A. Observation points were observed by WDFW, during 2014-2018. Total points included for data set A is 188.*

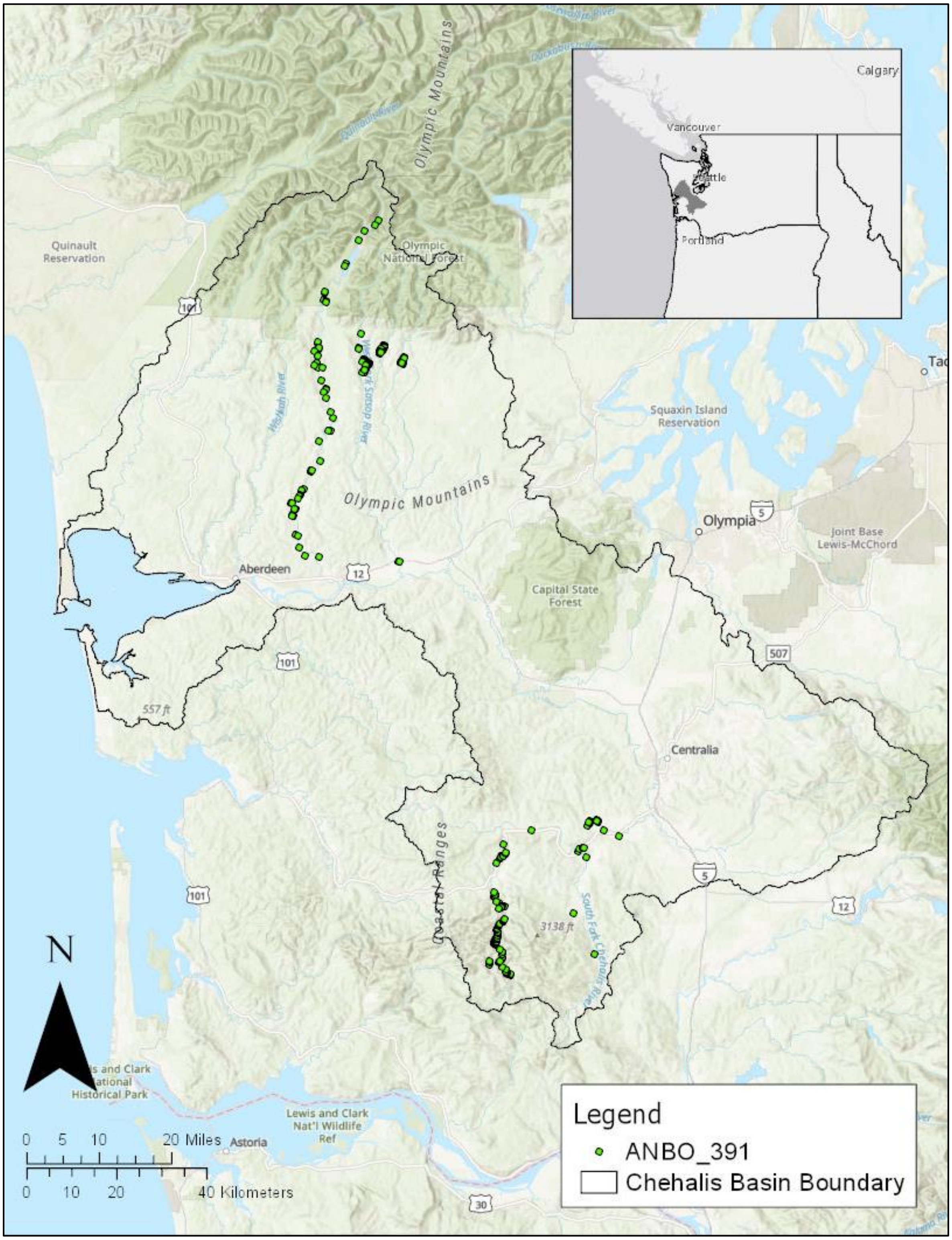

Figure 8*. Study Area with Dataset B.*

Covariates: Environmental Data

Table 2. *Derived Variables for the Suitability Index*

<table>
<tr><th colspan="2">Environmental Variable</th><th>Original Resolution</th><th>Source</th><th>Reference</th></tr>
<tr><td colspan="2">Percent Tree Cover</td><td>1arc-sec
(30 m)</td><td>2011 National Land Cover Data</td><td>U.S. Geological Survey, 20140331, NLCD 2011 Percent Tree Canopy, 3 x 3 Degree: NLCD2011_CAN_N45W120: U.S. Geological Survey.</td></tr>
<tr><td colspan="2">Land Cover</td><td>1arc-sec
(30 m)</td><td>2011 National Land Cover Data</td><td>U.S. Geological Survey, 20141010, NLCD 2011 Land Cover (2011 Edition, amended 2014), 3 x 3 Degree: NLCD2011_LC_N45W123: U.S. Geological Survey.</td></tr>
<tr><td colspan="2">Percent Land Development</td><td>1arc-sec
(30 m)</td><td>2011 National Land Cover Data</td><td>U.S. Geological Survey, 20141010, NLCD 2011 Percent Developed Imperviousness (2011 Edition, amended 2014), 3 x 3 Degree: NLCD2011_IMP_N45W120: U.S. Geological Survey.</td></tr>
<tr><td rowspan="4">Climate</td><td>Precipitation</td><td rowspan="4">30 arc-sec
(1 km^2)</td><td rowspan="4">Prism World Clim database</td><td rowspan="4">Fick, S.E. and R.J. Hijmans, 2017. Worldclim 2: New 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology</td></tr>
<tr><td>Temperature</td></tr>
<tr><td>Water Vapor Pressure</td></tr>
<tr><td>Solar Radiation</td></tr>
</table>

Environmental variables were chosen because of their potential influence on breeding occurrence. Percent tree cover, percent impervious surface, and land cover were retrieved from USGS Land Cover Data (NLCD 2011). I will explain why each NLCD layers was included and why they may be influential to Western toad breeding. Percent tree cover influences shading which may also impact attractiveness of riverine habitat to toads. Normally, toads prefer open landscapes for oviposition with little shading. Percent impervious surface is an interesting variable that I chose to include because of the impact human infrastructure may have on amphibian populations. With the increase of impervious surfaces such as roads and building hydrological impacts can affect surrounding rivers and streams. Land cover is a layer that categorizes the land types. I included this to see if there were any specific trends of land cover type.

Global Climate data was retrieved from World Clim 2. Climatic variables are at an initial spatial resolution of 30 seconds (~1km^2) (Ficks, Hijmans, 2017). There are 18 available climate variables, I chose to include 4 climatic variables because many of the available variables were not necessary to understand landscape characteristics. The climatic variables I thought that would be valuable for this local-scale project were solar radiation (kJm^{-2}), average temperature (°C), average precipitation (mm), and average water vapor pressure (kPA). I included these four varibles because I suspected they would add valuable information that may have not been present in the 14 other climate variables. Averages of temperature, solar radiation, precipitation, water vapor pressure are the most applicable to answering my research question of landscape scale factors that influence Western toad breeding.

Covariates: Layers

All layers included in this analysis were processed through GIS Arc Map 10.5. Transformation of geographic coordinate systems (GCS) was necessary, along with resolution scale changes. Below are the results of all layers which are processed in the same manner (Figure 9-15). NLCD (2011) data required geographic coordinate system transformations to match WorldClim data (version 2). Resolution for all layers is 30 arc-sec (~1 km^2). Below are raster layers included for this analysis in the same format used to run though *MaxEnt* application. Processing the raster layers was a lengthy process, but it was imperative to have virtually matching raster layers (same cell size, resolution, pixels, geographic coordinate system) for the modeling analysis. Below are the raster layers post processing with the same virtual dimensions all containing valuable information (Figure 9-15).

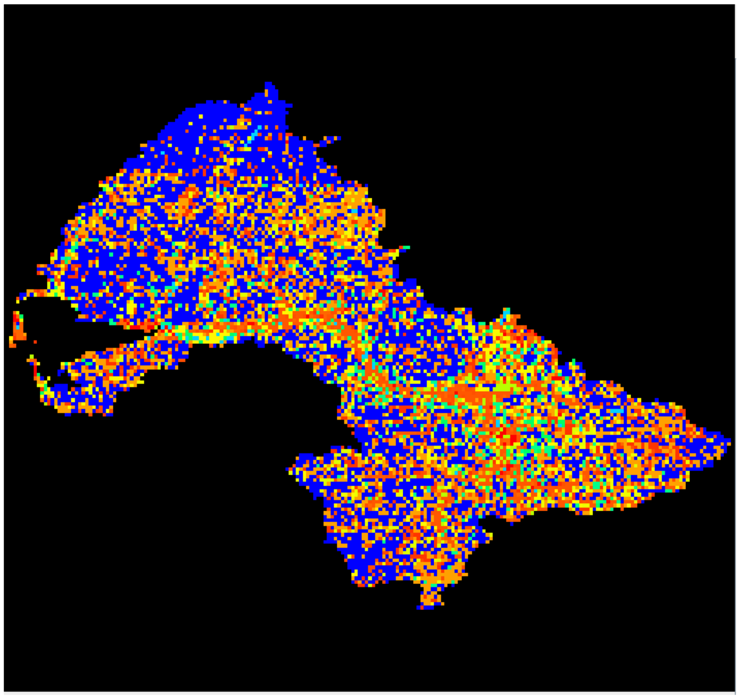

Figure 9. *Land Cover Retrieved from USGS NLCD 30-m Landsat-Based land cover database. Land classification with a 16-class legend.*

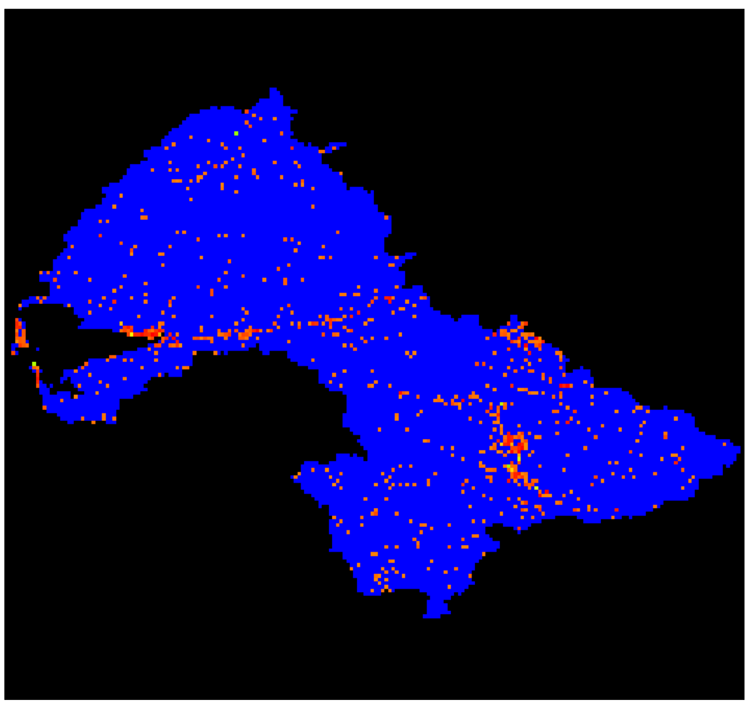

Figure 10. *Percent Impervious Retrieved from USGS NLCD. Percent Impervious represents urban impervious surfaces as a percentage of developed surface over every 30-m pixel.*

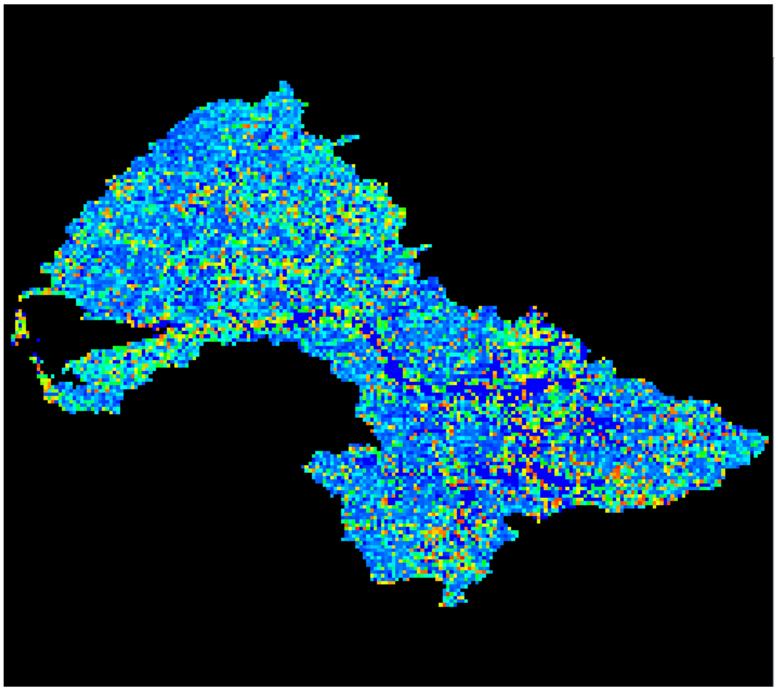

***Figure 11**. Percent Tree Cover Retrieved from USGS NLCD 30-m raster geospatial dataset containing percent canopy cover in a continuous number.*

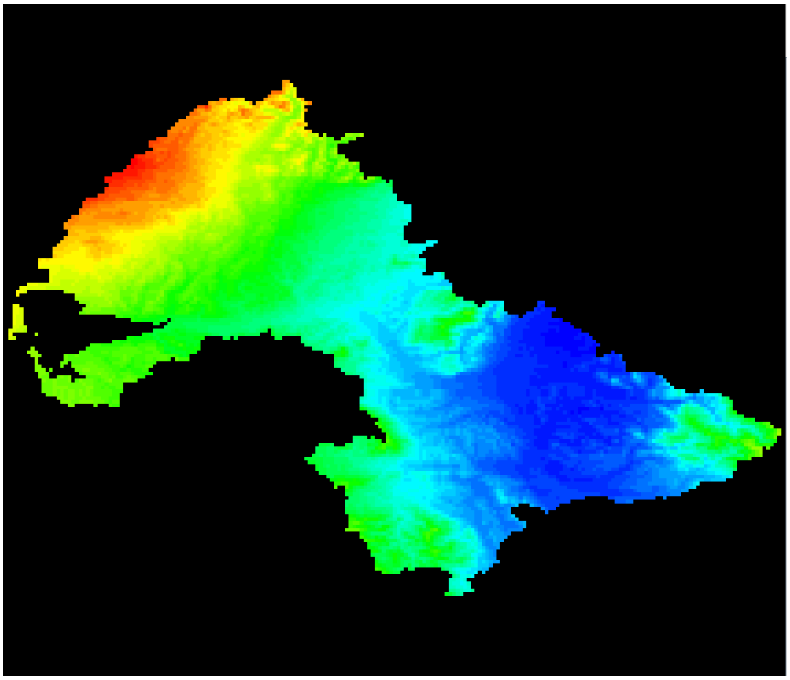

***Figure 12.** Average Precipitation from WorldClim Version2 monthly average from 1970-2000. This is a heat map with blue representing low precipitation levels red representing high levels.*

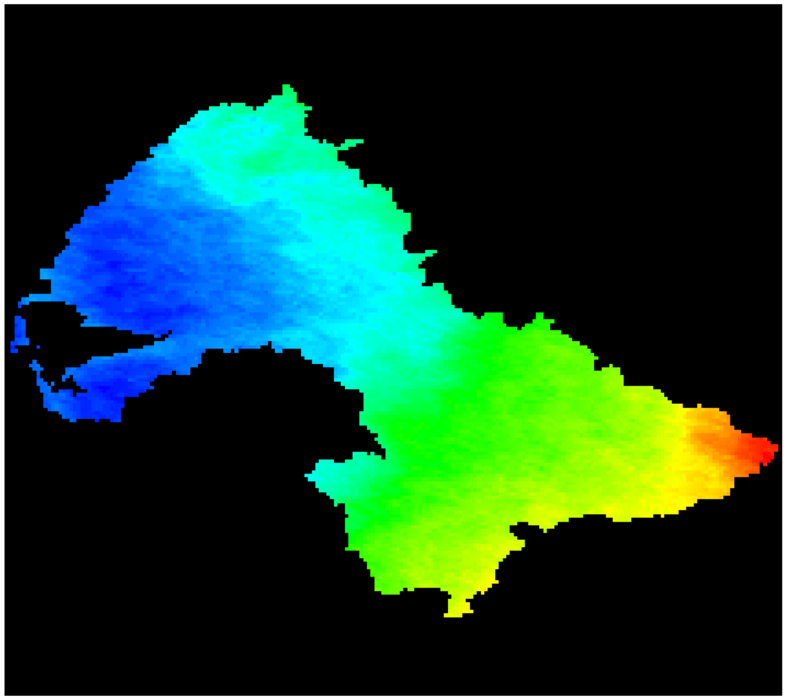

Figure 13. *Average Solar Radiation from WorldClim Version2 monthly average from 1970-2000. This is a heat map with blue representing low levels and red representing higher solar radiation.*

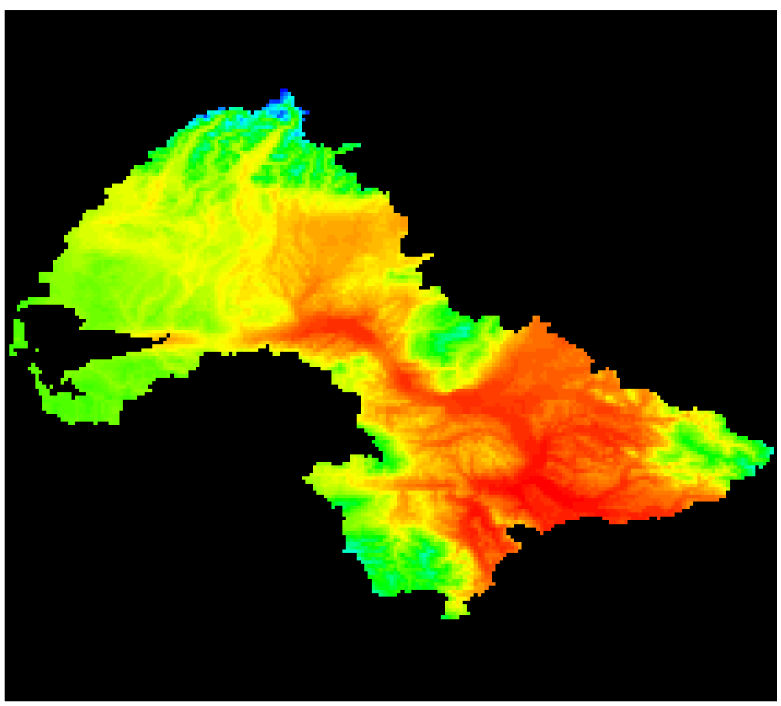

Figure 14*. Average Temperature from WorldClim Version2 monthly average from 1970-2000. This is a heat map with blue representing low levels and red representing higher temperature.*

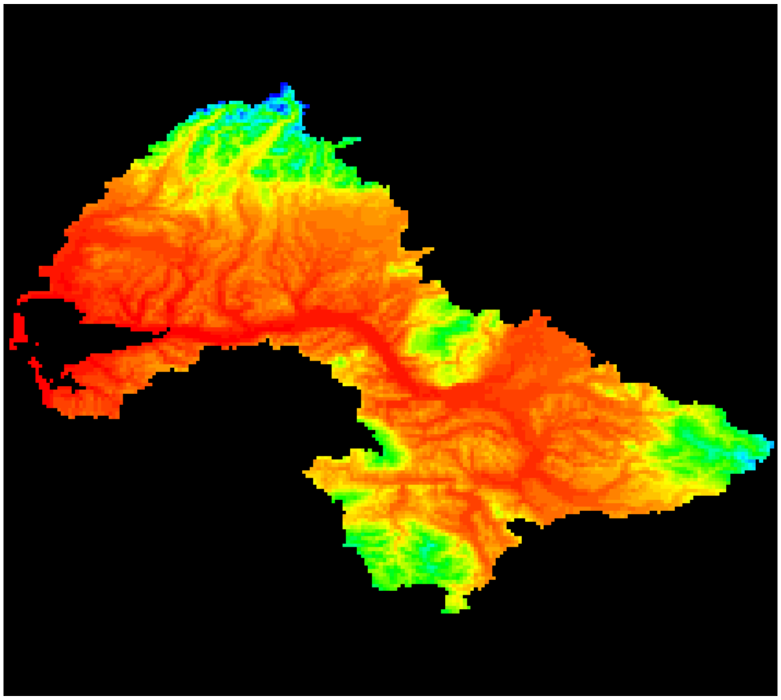

Figure 15. *Average Water Vapor Pressure from WorldClim Version2 monthly average from 1970-2000. This is a heat map with blue representing low levels and red representing higher water vapor pressure.*

MaxEnt: Application for Western Toad Breeding Distribution

This project utilized *MaxEnt* modeling to explore the relationship between species distribution and suitable habitat for the Western toad along the Chehalis River and its major tributaries. The purpose of *MaxEnt* modeling technique is the ability to predict which areas within the Chehalis River satisfy the requirements of the Western toad's ecological niche, specifically relating to oviposition. Model performance will be evaluated by use of *Area under the curve* (AUC), a commonly used accuracy measure for ENM and other SDMs (Phillips S. J., & Dudík, M., 2008). The GIS application ArcMap 10.5 was developed by Environmental Systems Research Institute (ESRI) and was used for layer processing. When the dataset was entered through *MaxEnt*, I manually set the random test percentage to 30%. By doing this, I partitioned the data into two groups; training (randomly, 70% of data used for validating) and testing (randomly, 30% of data used for evaluation). Training data contributes to the making of the model while testing is used for mode performance. Model performance will be assessed with the area under a ROC curve (AUC). ROC is the omission and receiver operating characteristic analyses. Seven environmental variables were extracted to predict and produce continuous suitability maps ranging from 0 (unsuitable) to 1 (optimal).

Results

Maxent Current Distribution

Western toad breeding distribution was focused in two main clusters within the Chehalis Basin. This can be attributed to certain environmental factors that influence habitat suitability and attractiveness. Monthly averages of solar radiation, precipitation, water vapor pressure, and temperature were all included to understand slight seasonal changes within the usual span of Western toad breeding. NLCD layers also added further depth into understanding what landcover factors influence Western toad breeding. Out of the seven variables included in this analysis, the variable that was present in all months as a leading factor was precipitation. Influence of each variable will be further explained in the section *Raw Data Outputs and Control Parameters*. In all months included in this analysis, precipitation was in the highest 3 variables in percent contribution. I included data (monthly averages) for the months of June, July, and August to understand the seasonal changes that can occur within a three-month span. There were slight differences in leading influential variables but the common four that were constantly present in percent contribution were precipitation (bio_precipitation), solar radiation (bio_solarradiation), and water vapor pressure (bio_watervaporpressure). These variables were in the top three influential variables in at least two of the models.

I was successful in running *MaxEnt* models for late spring/summer months to better understand slight shifts in the model outputs. Western toad breeding, oviposition, and larval rearing have occurred from June to August according to observations of WDFW (Hayes, Tyson, Douville, & Vadas, 2018). Knowing the range of breeding occurrence by WDFW observations influenced my decision to include the three months in this paper. Previously mentioned in the literature review, larval rearing occurs within about 45 days post oviposition, egg laying can occur in as short as a span of two weeks (Biek, Funk, Maxell, & Mills, 2002, Olson, Blaustein, O'Hara, 1986). This is further indication that oviposition and rearing windows are closely timed. Because of the overlap of timing between these phases monthly variation may serve as valuable comparison. Figures 17, 20, & 21 show slight variation within the three-month span most notably, during the month of July. July has a higher probability of containing suitable breeding/rearing habitat around the Grays Harbor shore. A lesser prediction occurs in June and in August this area is indicated as a lower probability of suitable habitat occurring.

Observation points of Western toad breeding/oviposition generally show two main areas within the Chehalis Basin where toads have historically been found (Hayes, Tyson, Douville, & Vadas, 2018). My results are able to better explain why toads breed in these two areas and how they may differ with other areas within the basin. An overview and breakdown of model performance will be discussed in the next section. Generally speaking, it is noteworthy to mention all the model projections for June, July, and August received "good" to "excellent" AUC values according to the standards established by Swets (1988).

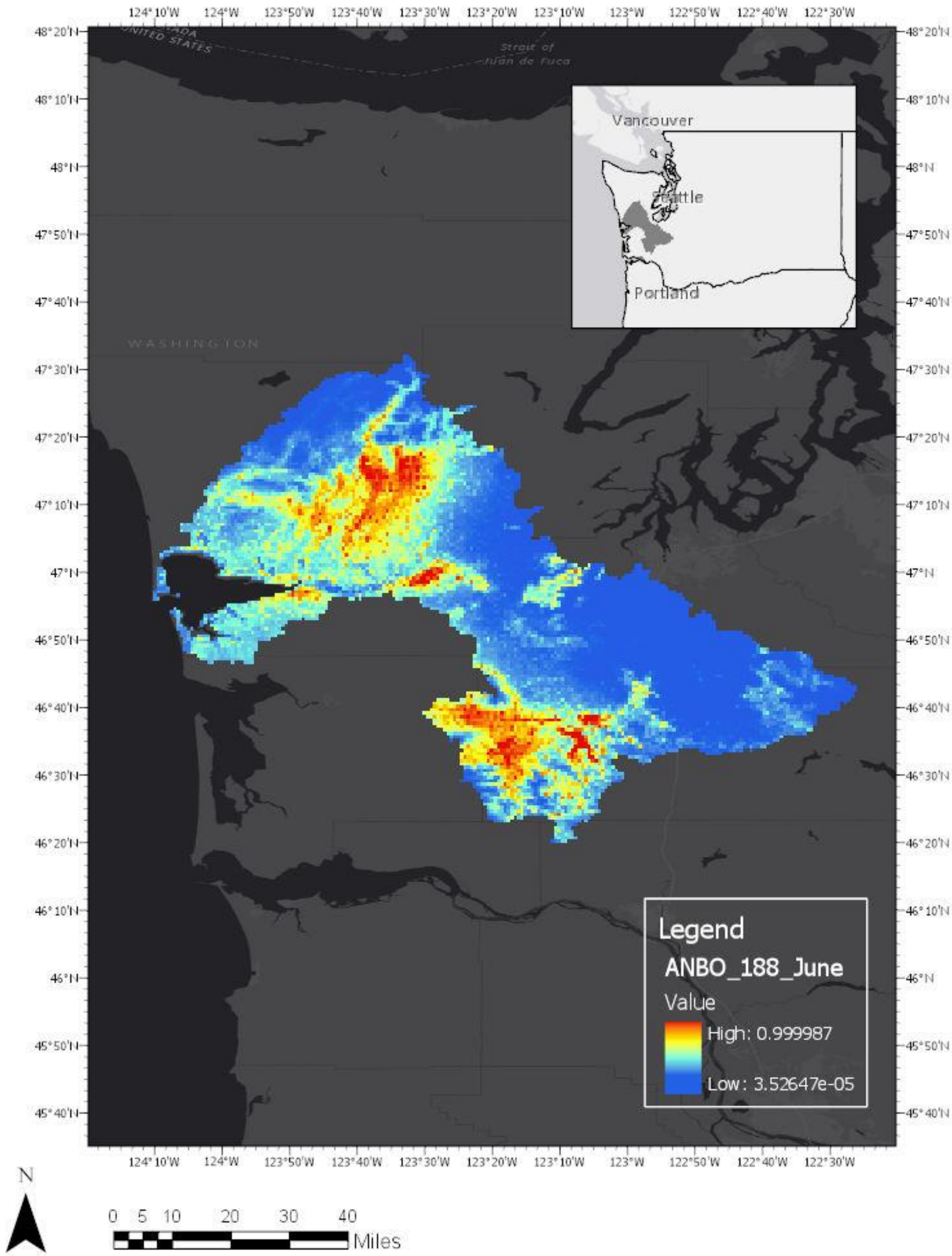

Figure 16. *MaxEnt Output for June using Dataset A. All seven environmental and climate variables included for this analysis.*

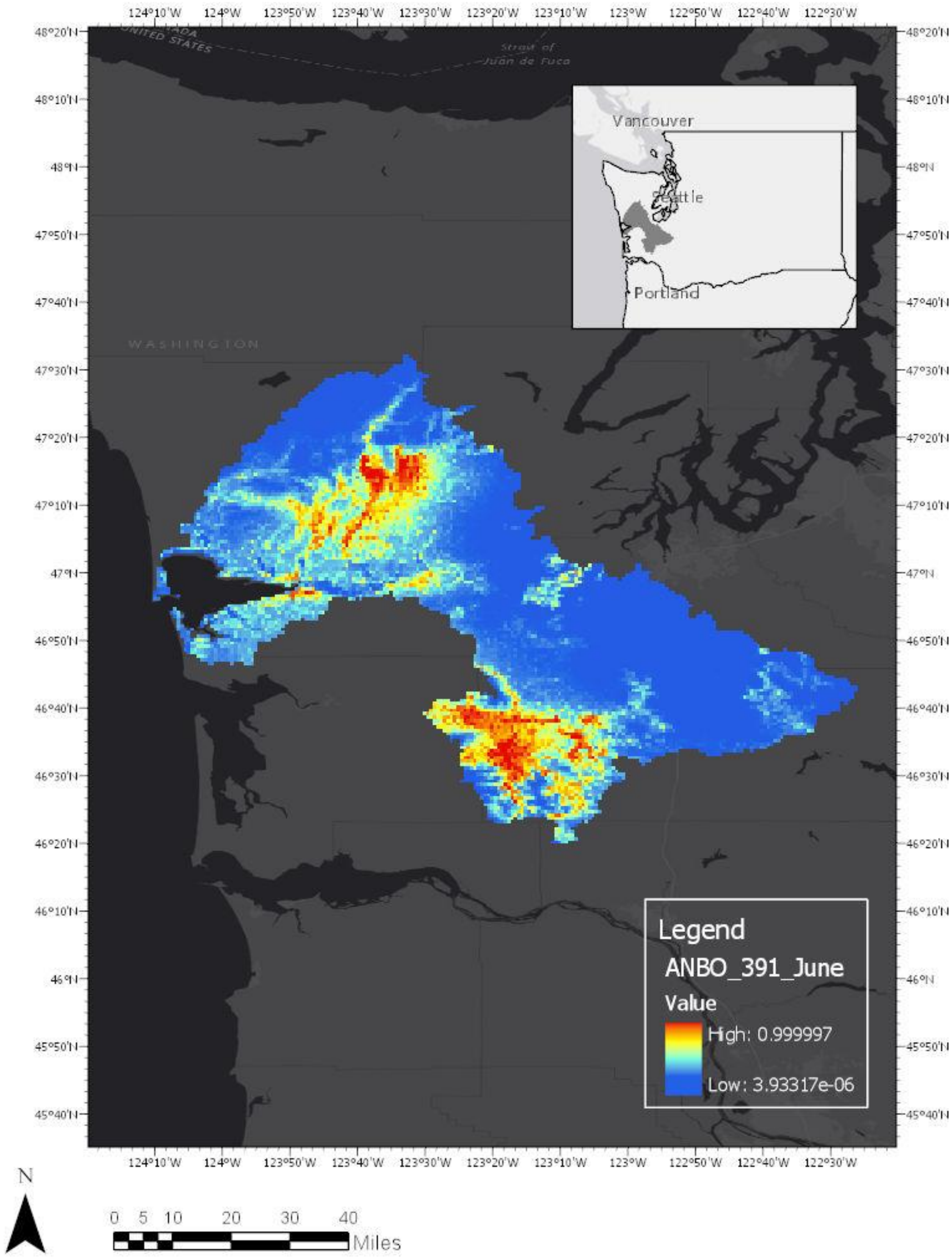

Figure 17. *MaxEnt Output for June using Dataset B. All environmental and climate variables included for this analysis.*

Model Performance

I considered it more important to incorporate all tadpole, egg mass, and adults found in amplexus localities to decrease the chance of overfitting the data. Overfitting is a common issue with *MaxEnt* that can be decreased with better sample data (random, geographically/spatially random, and increased numbers of sample). By increasing the locality points I included (using Dataset B with 391 points), I also increased the quality of prediction. This was done by choosing the model output that had an omission rate (test and training) that were as close to the predicted omission rate (Figure 18 and 19). Notice that the first model, which included dataset A, has a bigger gap between the tested and training omission rate than in the model produced with dataset B. The test (light blue line) and training (dark blue line) omission rate should be close to the predicted omission (black line), because of the definition of the cumulative threshold.

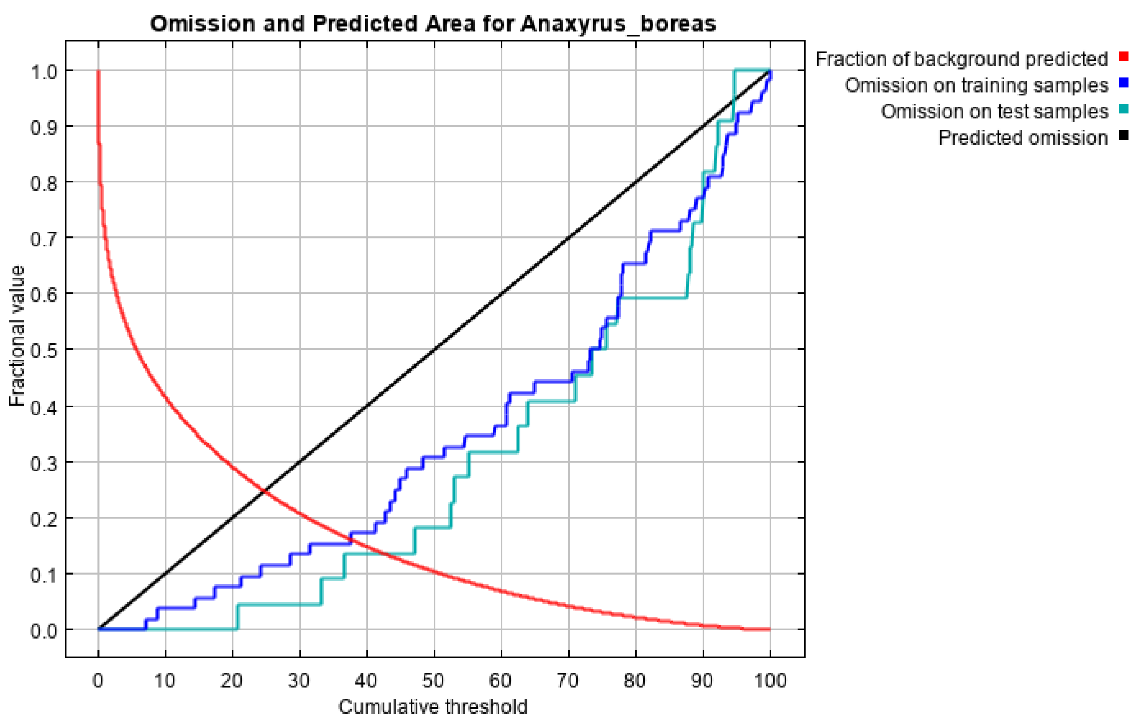

Figure 18. *Omission Rate of the Model using Dataset A for the month of June.*

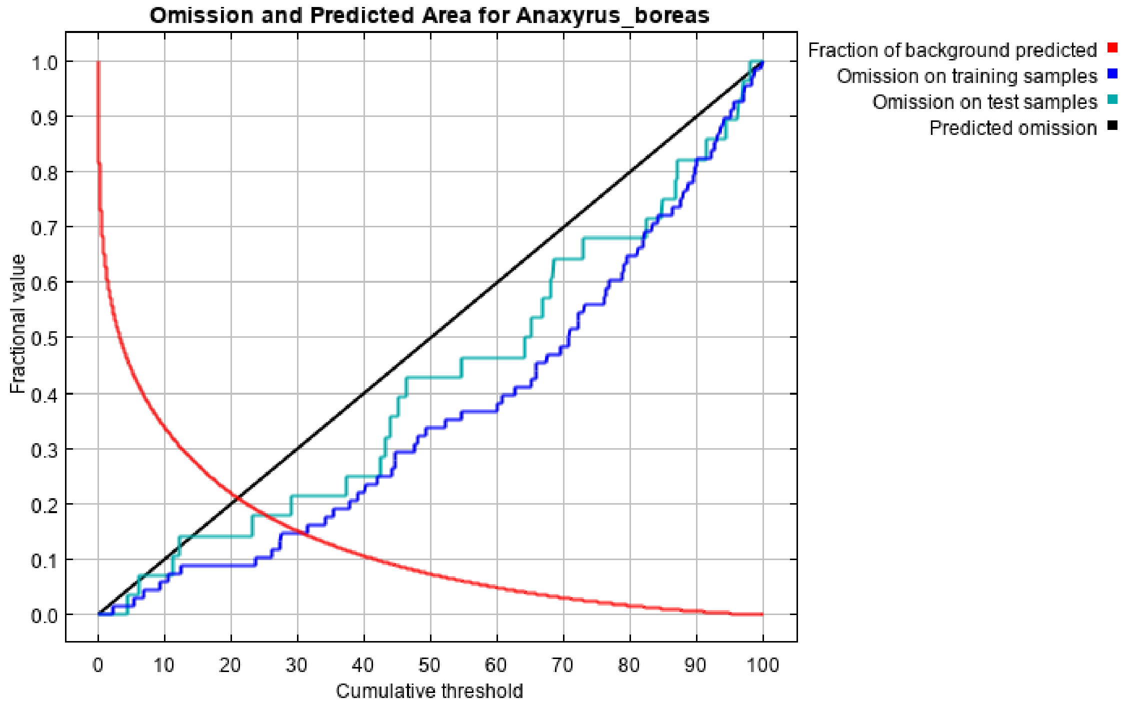

Figure 19. *Omission Rate of the Model using Dataset B for the month of June.*

According to the above figures, the dataset containing more occurrence points (391- dataset B) for the month of June, has a closer relation to the predicted omission line (Figure 19). This indicates that the model created (Figure 17) has a higher predictive ability than the model using dataset A (Figure 16).

Essentially, these graphs illustrate the higher predictive ability of the model when using Dataset B. Leading to my decision of using Dataset B for the rest of the analysis because it serves as the better option to limit overfitting. Without going through the process of creating two datasets to compare performance I may have limited my results unknowingly. If I used Dataset A exclusively, I may have limited my results to inaccurate projections of suitability as well as lead to incomplete or vague inferences of the results.

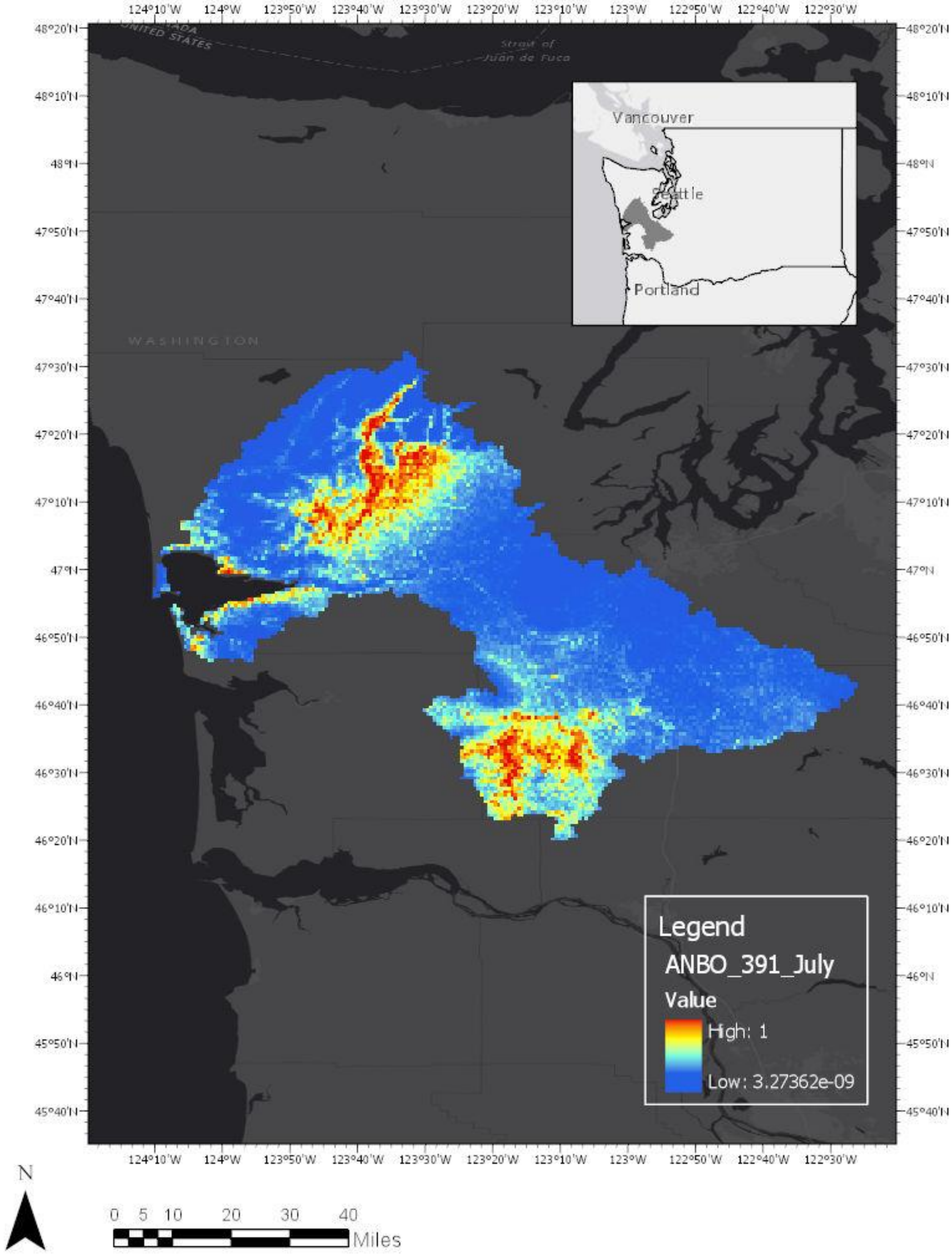

Figure 20. *MaxEnt Output for the month of July. Using Dataset B.*

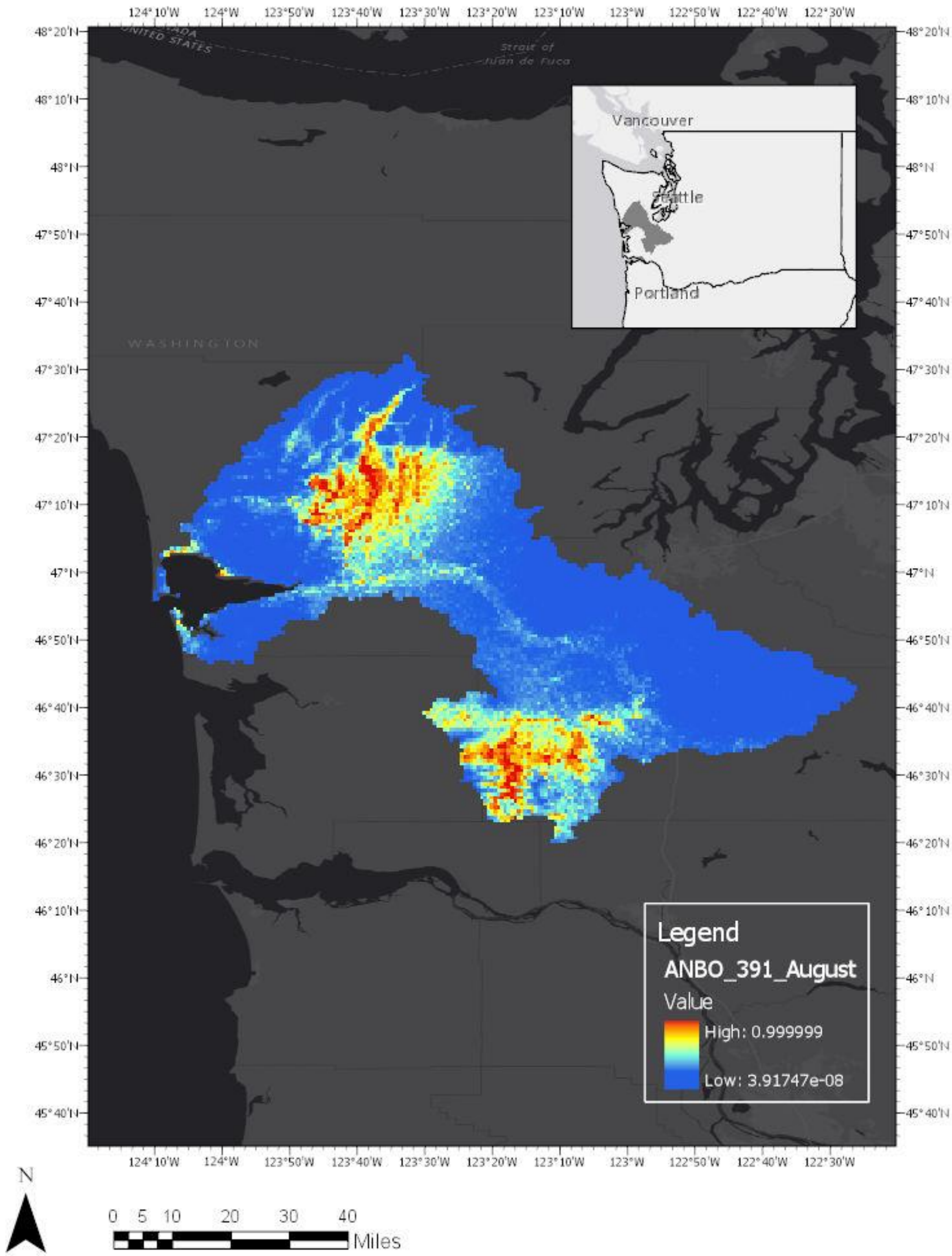

Figure 21. *MaxEnt Output for August. Using Dataset B.*

Raw Data Outputs and Control Parameters

For several reasons, Dataset B was considered the better option to accurately represent toad breeding distribution within the Chehalis Basin. Whenever possible including as many points to the dataset is beneficial to the model by more accurately representing the realized distribution of a species. This should not compromise the quality of points (uncertain identification points should be excluded). I concluded by including all localities of tadpoles at all stages increased the dataset without compromising the model output. As tadpoles develop, they also become mobile and can move from original oviposition location; however, literature has not proved that tadpoles move significant distances from oviposition areas. For this research purpose I will consider breeding and rearing locations as similar enough to include all larval occurrences. I am confident that including all tadpole data in my analysis allowed for more essential inferences on Western toad breeding based on model outputs.

For the month of June using Dataset B, an AUC_{test} was calculated at 0.902 ± 0.024 (Figure 22) (calculated as in Delong, Delong & Clark-Pearson, 1988). This means that the model has a fairly high predictive power. A random model has an AUC of 0.5 while the closer to 1.0 means the model increases in predictive capability. The following settings were used during the run: 68 presence records used for training while 28 for testing. 10007 points were used to determine the *MaxEnt* distribution. The algorithm was terminated after 500 iterations (1 second). The sensitivity vs. specificity graph, found below, is the receiver operating characteristic or the (ROC) curve (Figure 22). The specificity as defined here is using the predicted area, rather than the true commission. This means that the maximum AUC achievable is less than one.

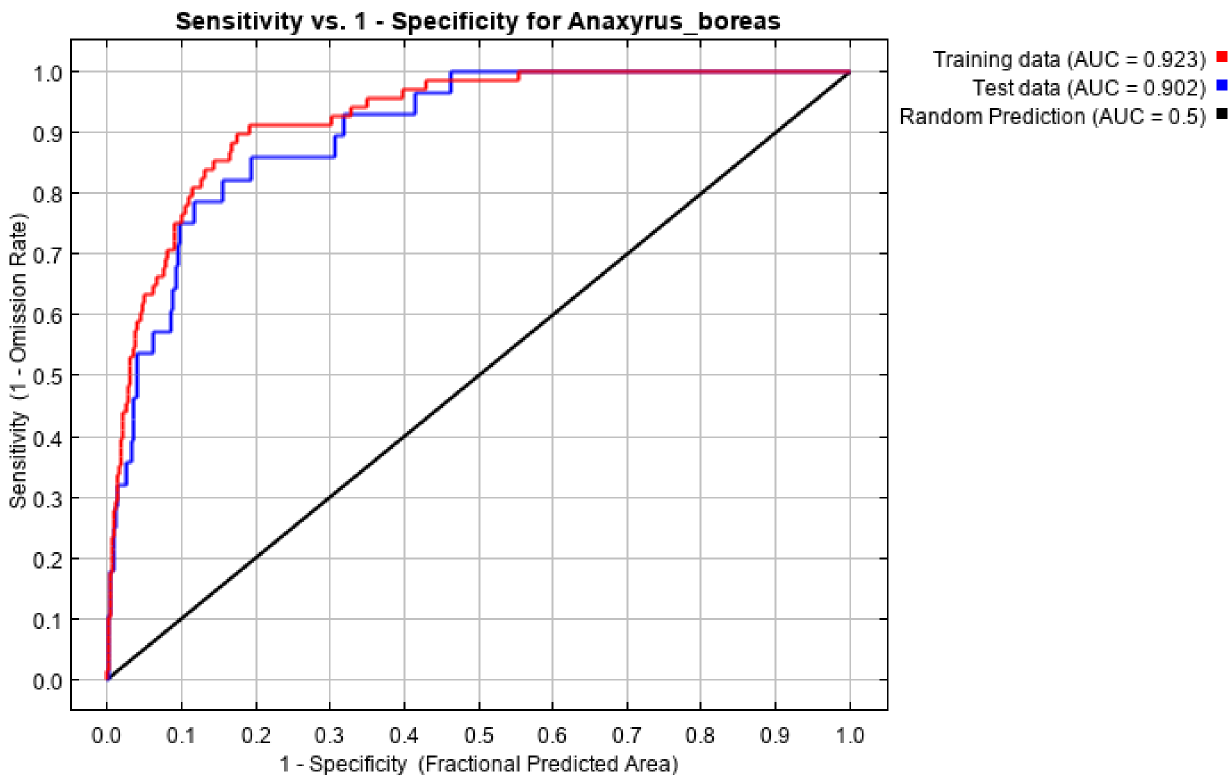

Figure 22. *Sensitivity Versus Specificity for Anaxyrus boreas for June.*

These results show that the model produced (Figure 22), were significantly better than at random when tested for the omission and ROC analysis. An AUC_{test} at 0.902 is a fairly "good" value, above 0.900 is the threshold for a "good" reading (Swets, 1988).

For the month of July, model projections had an AUC_{test} of 0.934 ± 0.019 (Figure 23) (calculated as in Delong, Delong & Clark-Pearson, 1988). The following settings were used during the run: 68 presence records used for training, 28 for testing. 10007 points used to determine the Maxent distribution. Algorithm terminated after 500 iterations (1 seconds). This is another "good" AUC value.

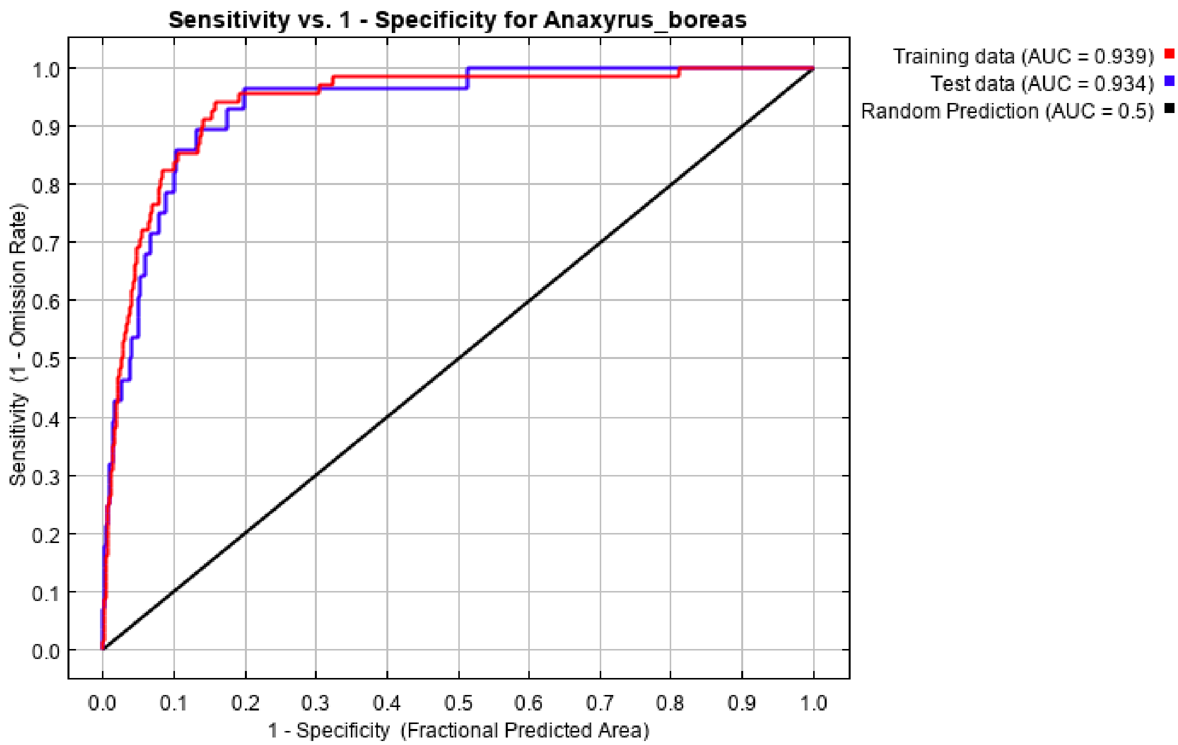

Figure 23. *Sensitivity Versus Specificity for Anaxyrus boreas for July.*

August model projections had an AUC_{test} of 0.947 ± 0.011 (Figure 24) (calculated as in Delong, Delong & Clark-Pearson, 1988). This was the model with the highest test AUC value. The following settings were used during the run: 68 presence records used for training, 28 for testing. 10007 points used to determine the Maxent distribution. Algorithm terminated after 500 iterations (1 seconds). August had the highest AUC_{test} value, indicating that the model projections for the month of August has the best performance of all other model projections. This is not to say that the other months do not offer valuable information or have performed badly; it just indicates that the August model has stronger prediction ability and an “excellent” AUC value.

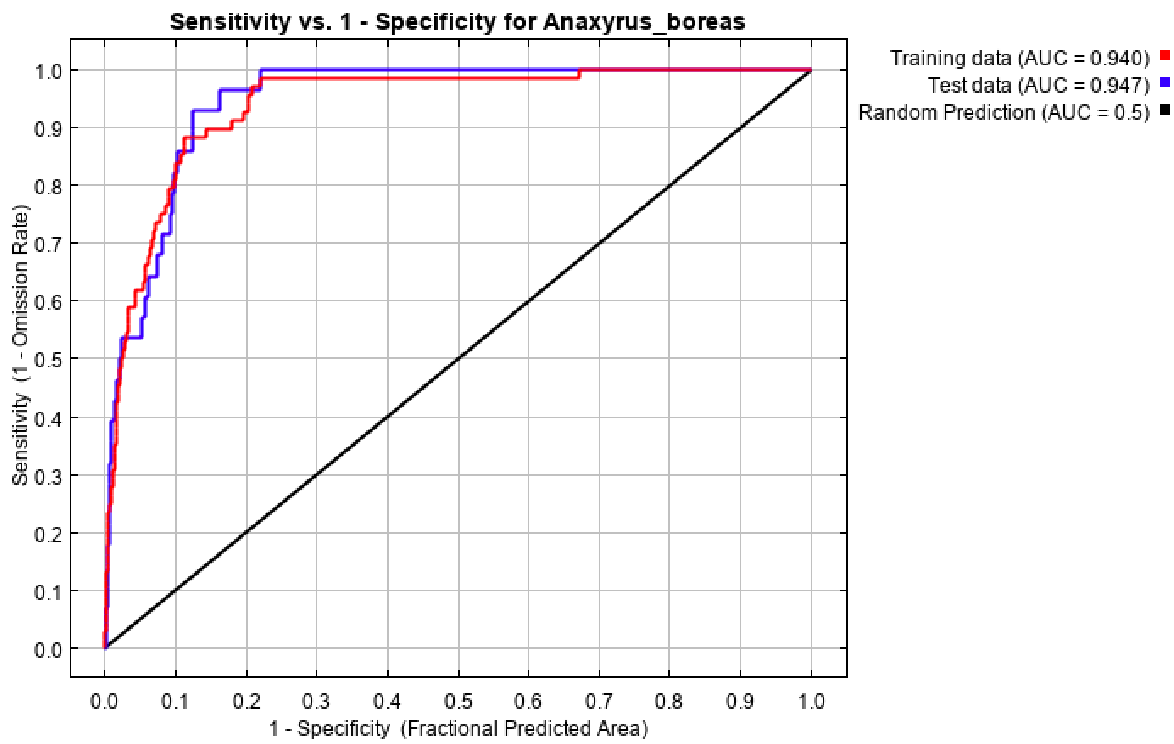

Figure 24. *Sensitivity Versus Specificity for Anaxyrus boreas for August.*

<u>Jackknife Analysis: June</u>

Jackknife analysis essentially indicates the environmental variables that have the most influence on the model projection. Jackknife analysis compares environmental variables with the highest gain when used in isolation to the training dataset. For the models using monthly averages for June and July, precipitation (bio_precipitation) was the variable with the highest gain when isolated. This was also true that precipitation decreased the overall gain the most when it was omitted. This indicates that precipitation appears to have information that is not found in the other variables. Notice that for June, precipitation, solar radiation (bio_soalrradiations), and temperature (bio_termperature) are the most influential variables (Table 3). Precipitation had 56.1% contribution while solar radiation had 18.3 and temperature with 17.4%.While water vapor pressure (bio_watervaporpressure), land cover (bio_landcover), percent impervious (bio_percentimpervious), and percent tree cover (bio_percenttreecover) show virtually no contribution (under 10% of a contribution).

Variable	Percent contribution	Permutation importance
bio_precipitation	56.1	58.6
bio_solarradiation	18.3	12.3
bio_temperature	17.4	24.1
bio_watervaporpressure	3.8	3.9
bio_landcover	3.6	0.8
bio_percentimpervious	0.8	0.3
bio_percenttreecover	0	0.1

Table 3. *Environmental variables with the contribution for June each has on the module while using dataset B.*

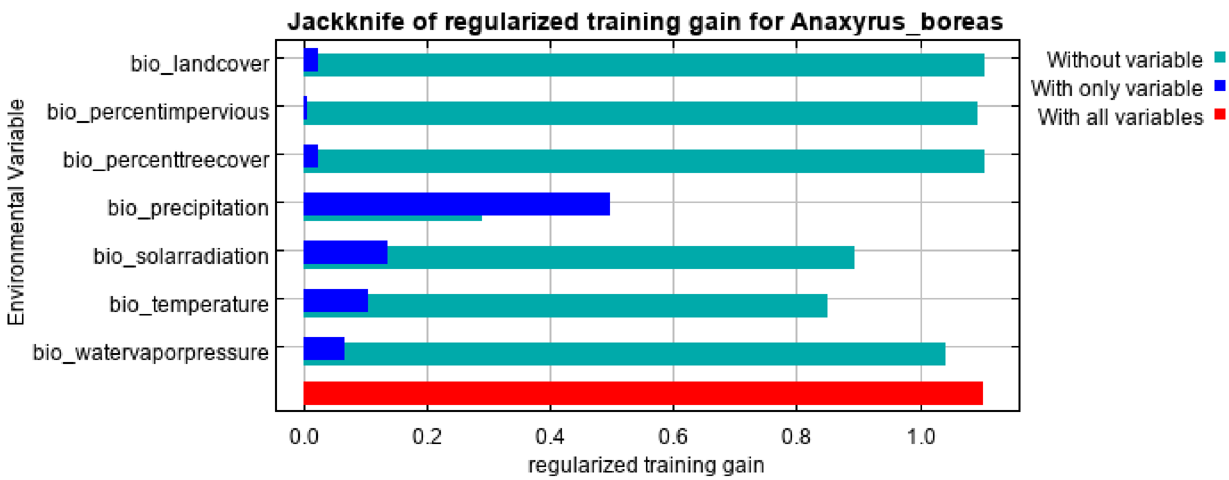

Figure 25. *Jackknife of Regularized Training Gain for June*

<u>Jackknife Analysis: July</u>

July was also similar to June, in that precipitation and solar radiation were the leading variables with the highest amount of influence. Precipitation had a 45.2 percent contribution while solar radiation had 29.8%. However, the third leading variable was water vapor pressure (bio_watervaporpressure) with a percent contribution of 18.1%. The variables that influenced the model projection the least for July were percent tree cover, percent impervious, temperature, and land cover (all with less than 10% contribution).

Variable	Percent contribution	Permutation importance
bio_precipitation	45.2	38.2
bio_solarradiation	29.8	34.9
bio_watervaporpressure	18.1	23.5
bio_percenttreecover	4	1.6
bio_percentimpervious	1.3	0.5
bio_temperature	1.2	1.1
bio_landcover	0.4	0.2

Table 4. *Environmental variables with the contribution for July while using Dataset B.*

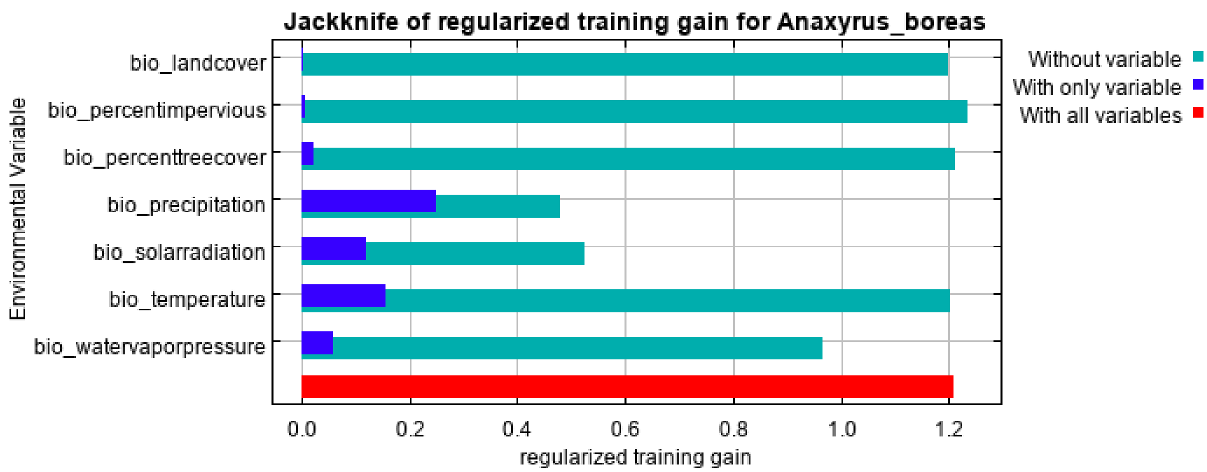

Figure 26. *Jackknife of Regularized Training Gain for July while using dataset B.*

<u>Jackknife Analysis: August</u>

All the models included in this research had good performance and show interesting variances between summer months and the variables that may influence Western toad breeding. The leading variables with the most influence of model prediction for August were solar radiation, precipitation, and water vapor pressure. Solar radiation and precipitation had the same percent contribution at 37.2%. Water vapor pressure had 16.4% of contribution. The variables with the least influence for August are temperature, percent tree cover, percent impervious, and land cover (all with less than 10% contribution).

Variable	Percent contribution	Permutation importance
bio_solarradiation	37.2	34.4
bio_precipitation	37.2	37.9
bio_watervaporpressure	16.4	23.9
bio_temperature	5	2
bio_percenttreecover	2.8	1.2
bio_percentimpervious	1.1	0.3
bio_landcover	0.3	0.3

Table 5. *Environmental variables with the contribution for August while using Dataset B.*

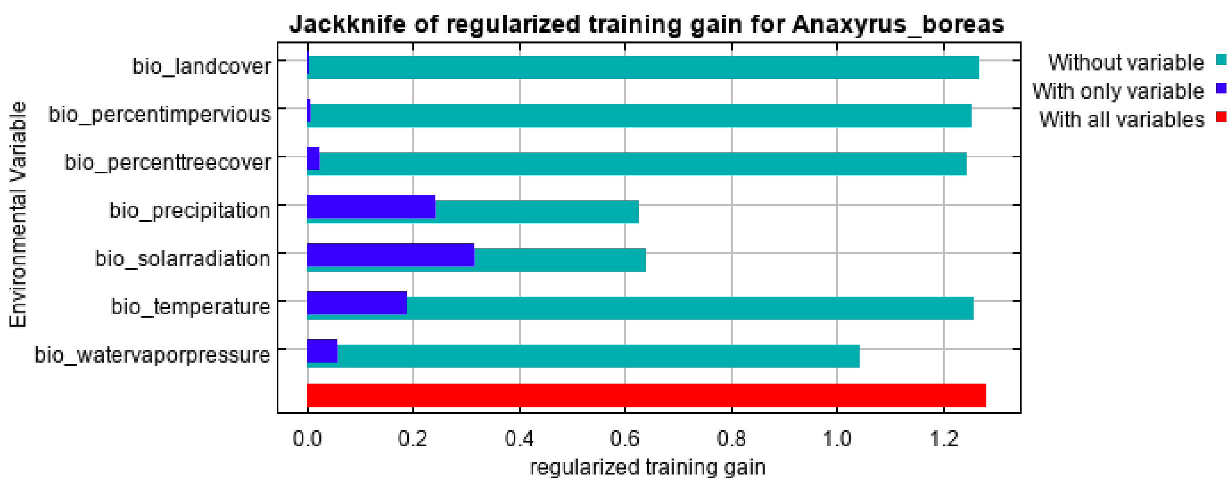

Figure 27. *Jackknife of Regularized Training Gain for August while using Dataset B.*

Overall, the variables that consistently showed influence on the model predictions were precipitation, solar radiation, and water vapor pressure. Precipitation was one of the three influential variables in all models. This indicates that precipitation contains more information that is not present in the other variables. Further, making precipitation a variable to include in other *MaxEnt* analysis regarding Western toad distribution.

Discussion

Maxent Explanation:

With the success of running *MaxEnt*, I was able to produce habitat suitability maps for Western toad in the Chehalis Basin. Results for all models during the months of June, July and August indicate the most influential variables for suitability were precipitation, solar radiation, and water vapor pressure. Out of the seven variables that were included in my models, precipitation was found to have the most influence for all three months (56.6% for the month of June, 45.2 % for July, and 37.2 for August). No other variable was present in the top three influencing variables in all three models. This indicates that precipitation may hold significant influence on Western toad breeding.

Model predictions were able to identify new areas within the basin that may provide suitable breeding habitat during the month of June. This area is surrounding Grays Harbor, and may be similar enough to the pixels that contain known occurrence points which may indicate is an area suitable for oviposition during the June window. This can be confirmed by further investigation and surveying around these areas. The ability *MaxEnt* has to predict areas within the study area that may be suitable is an impressive and groundbreaking tool. Knowing and identifying areas within the Chehalis Basin that may be suitable for Western toad will aid in future conservation projects. Not only was I able to illustrate current breeding distribution in the Chehalis Basin, but I was also able to better understand how the environmental variables I included in this analysis may influence western toad breeding distribution.

It is important to note several limitations with this research. First, I obtained data from a couple different sources (Table 2) which required raster processing due to different resolutions, cell size, and conflicting geographic coordinate systems (Young et al., 2011). Conversion of the projection systems could have resulted in inadvertent error and should be considered. Raster processing is a lengthy process and typically the most time consuming in a *MaxEnt* workflow. This is due to the GIS skill required to understand and manage raster data. Many steps were included to conduct raster processing. Because I was using monthly averages for seven variables for a three-month span, I ended up processing 21 raster layers. To run the *MaxEnt* application, it took one second for model completion, but many hours of raster processing preceded this simple one-second model computation. During raster layer processing there may be further room to use existing raster layers and advanced GIS skills to further manipulate raster layers (slope, elevation, etc.).

Second, when snapping the environmental raster layers to ensure they would run properly through *MaxEnt*, I had to upscale variables that were derived from 30-meters to represent proportions in 1000-meter cells (Dilts, 2015). There were various reasons for this step, but the most important was that all raster layers need to have some dimensions, including resolution. Fine-scale resolution may be an option in the future. Further fine-scale models (at 30-m) may provide more accurate information considering the size of the study area in this research. When presented different resolutions (of raster layers) it is common to change them to match the highest resolution out of all the layers. It is advantageous to keep layers at the coarser scale (1km) resolution rather than fine-scale (30m) so that raster layers would accurately represent the data. Raster data can go from fine to coarse but may lose data integrity from going from coarse to fine. It is also more informative to have neighborhood (cells) information rather than an actual value for an individual cell.

Third, while the results show a habitat suitability index of the Chehalis Basin, it is important to note the results indicate general locations of suitable breading and rearing habitat. These may be correlated in areas of high-density occurrences; I did not account for this when producing the models. This is also tied to the fact that Western toad surveys were not conducted randomly, leaving the possibility of sample selection bias potentially interfering with the SDM assumptions (Phillips, 2008). This can be corrected or further accounted for by using more in depth *MaxEnt* regularization settings. This brings me to my next caveat, when running *MaxEnt* I used the automatic settings due to the type of modeling I was conducting, certain setting may have been more beneficial. Due to time constraints I was unable to dive in the depth of *MaxEnt* settings.

Finally, in this analysis, I did not include information regarding streams, riverbanks, and wetlands, which would have required significant information/data on stream hydrology. This led to the lack of stream characteristics included in this analysis and, subsequently, painting suitable habitat for Western toad with broad strokes. Future studies would provide better understanding of the hydrological variables and how they influence breeding. Much of this data is being calculated by stream models with information derived from stream gauges. Due to time restrictions, I was unable to include in depth stream data such as slope, stream temperature, velocity, etc., into my models. This should be included in future *MaxEnt* modeling for Western toad.

<u>Potential Changes in Analysis:</u>

This research is an introductory project utilizing *MaxEnt* species distribution model to deepen our understanding of Western toad breeding on a local scale. The goal to understand landscape scale factors and how they may influence breeding has been achieved, but there are still ways to improve upon this research. WDFW, whom contributed the locality data for these models, may be able to utilize *MaxEnt* methods in future projects to map and understand habitat suitability for a range of species. I suspect that *MaxEnt* will only continue to gain popularity and use because of the valuable information you can gain about a species distribution. This study serves as a valuable example of things done well and has the opportunity to be fine-tuned for future projects. However, there are several aspects that should be addressed in future projects. I will present the major caveats and potential solutions in this portion of the discussion.

If I were to do this project again and time was not a constraint, I would change several aspects. There is a lack of bias control in my methodology and this may have influenced the models I created. If I were to do this again, I would pay closer attention to the locality data. I would delete points that are close together to avoid areas labeled as high prediction (red areas on the suitability index maps), as they may correspond with high density Western toad occurrences. This may have led to the two separate clusters on the map, namely, the upper Chehalis near the Skokomish, and the lower Chehalis near Centralia. An important note about thee observation data is that not all areas in the Chehalis have been surveyed, this may result with more toads in reality than the data represents.

MaxEnt has automatic settings that can offer very fine-tuned model predictions. The automatic settings of *MaxEnt* may have worked for this study, but there are many regularization settings that may serve to strengthen future results. For the models I produced, I used *MaxEnt's* default regularization parameters. This may have consequently produced models that overfit the training data (Jiménez-Valverde et al., 2011). This brings me to one of major improvements to be made in the next study. Future studies of breeding parameters may include more stream related data such as stream gradient, flow, temperature, etc. This would allow a better understanding of breeding parameters and is a natural next step of this research, however, to do that it would require significant calculation of stream data. However, it might be difficult to map areas within a study area that include large portions of terrestrial areas (cells with no stream data would result in error). While still focusing on landscape-scale environmental factors, it would be interesting to look at distances proximate to impervious surfaces. I suspect that impervious surfaces play an important role in amphibian distribution. This relationship can be explored by looking more closely at buffers and proximity of impervious surfaces to Western toad populations.

Conclusion

MaxEnt is a common tool in conservation biology because of its open access status, range of application, and user-friendly interface. *MaxEnt* can provide useful information regarding a large geographic range. This project identified landscape-scale factors within a local geographic range, the Chehalis Basin. Further, *Maxent* analysis provides very important information that Washington State and other agencies will benefit from. *MaxEnt* is a very popular SDM and will continue to grow with the increasing need of species-specific information on endangered species and with invasive species moving into gaps where endangered species are quickly disappearing from. There is need for species-specific information and the interaction with environmental conditions at a range of spatial scales. *MaxEnt* is working on bridging this gap and can be used to infer information about the ecological characteristics that may be suitable for species of concern.

MaxEnt is based on the maximum entropy principle which is the estimation of an unknown probability distribution (over a study area), the least biased solution is the one that maximizes its entropy. *MaxEnt* works by taking input data that includes locality points in a csv file, raster layers of variables included in analysis, and background points within a defined study area. The output is a continuous map of suitability, scaling from zero to one (zero is unsuitable, and one is optimal). The output is essentially a habitat suitability index. *MaxEnt* is based on a set of complex algorithms used to make predictions and inferences with incomplete knowledge/information. *MaxEnt* identifies areas within the study area that have a high probability of suitable environmental conditions that are similar to known occurrence points.

There are many pros and several cons of using *MaxEnt* modeling technique for this research. Since *MaxEnt* is one of the few SDM techniques that use presence-only data it is often the best way to accurately map distribution. It is also much more reliable to use presence-only records compared to presence-absence due to false negatives resulting in a type II error. As mentioned previously, *MaxEnt* is easy to use and has automatic settings that allow for in depth analysis. It is important to note that presence locations do not always mean it is optimal environmental quality, this is not so much an issue with *MaxEnt*, but something to consider when using its methods.

One of the major concerns of *MaxEnt* is the issue of overfitting data. This should be considered in future projects and steps should be taken to avoid this whenever possible. Even though *MaxEnt* is an easy to use tool for mapping distribution, the results depend on the type of data you use as input. There is a common saying within the machine learning community: models without data are not compelling while data without models' lack information. This is true. In order to understand population implications of habitat loss or destruction it is necessary to assess how multiple factors interact with each other and influence population dynamics.

MaxEnt is a great resource for informing management decisions because of its impressive model outputs that clearly indicate high probability of suitable habitat and areas with low probability of suitable habitat. Predicting areas of suitable habitat for a specific species is essential in making management decisions. This research was able to produce models that show two distinct portions of the Chehalis Basin that have reached the requirements needed for Western toad breeding and egg rearing. By better understanding some landscape scale factors and the way they influence Western toad breeding WDFW can take this information and use it to further understand Western toad distribution on a local scale. Effective conservation is a goal that many researchers at WDFW strive for and can be achieved with incorporating distribution modeling techniques. Effective conservation requires species-specific predications that can be applied to unique situations on a range of different scales, systems, and situations. This is one of the main reasons I chose to tackle this project while using *MaxEnt*, because of its robust ability and excellent performance compared to other techniques such as GARP (Elith et al., 2006).

Western toad breeding and rearing habitat is currently threatened with a proposed dam, if realized current breeding distribution may decline. This research has provided an estimation of current breeding distribution within the Chehalis Basin. There is a significant portion of suitable breeding habitat that is in the footprint of a proposed dam (Hayes, Tyson, Douville, & Vadas, 2018). Implementation of a dam may change suitability of habitat and may cause a decline in Western toad occupation in this basin. I suspect that with the implementation of a dam further fragmentation will occur. Environmental fragmentation comes with parallel population fragmentation which may eventually lead to the disappearance of Western toad from the Chehalis Basin.

This research identifies specific climatic variables as the leading influential factors in the projected suitability maps. An examination of the contribution of each environmental variable towards model prediction suggests that precipitation, solar radiation, and water vapor pressure were the highest influencing factors. These variables should not change with a dam implementation, but that is not to say there are environmental factors that were not identified here, but still play an equally or more important role on Western toad breeding. This research has indicated to researchers at WDFW that further *MaxEnt* analysis will be necessary to continue unveiling factors that influence Western toad breeding. Vulnerability of Western toad during one of the most critical life history stages should be addressed by WDFW in future plans and projects if implementation of a dam is what ensues.

Conservation efforts for Western toad should prioritize areas with high density of toad breeding and areas that have a higher probability of being attractive (and potentially suitable to toads). Decline and eventual loss of Western toad to the Chehalis Basin may be part of a larger trend in the Pacific Northwest and action must be taken to protect biodiversity to ensure healthy and resilient ecosystems in the future. Site specific action is necessary to prevent the loss of Western toad to the Chehalis basin. This can be achieved by implementing conservation plans at multiple spatial scales.

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