Stay salty: A sea louse (*Lepeophtherius salmonis)* population model for areas with strong fluctuations in daily salinity

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Statement of Purpose

The purpose of this thesis is to develop a differential equation to adequately model sea lice *Lepeophtheirus salmonis* population dynamics along the coast of Newfoundland and Labrador, and other locations with strong salinity fluctuations. Sea lice's growth is known to depend on temperature and salinity, and several models have been able to predict sea lice population dynamics (Hurford, Wang, & Zhao, 2019; Rittenhouse, Revie, & Hurford, 2016). However, Hurford *et al.* suggested that no sea lice should persist in Newfoundland and Labrador, which does not match reality (Hurford et al., 2019). Hurford *et al.* indicated that this might be due to significant daily fluctuations in salinity, not seen at other locations. Sea lice and other marine parasites are a significant issue for the aquaculture industries, leading to millions of dollars of economic loss as a result of reduced fish growth and increased mortality. Better management strategies would reduce the cost of treatments and decrease the environmental impact of aquaculture on surrounding ecosystems.

This primary goal of this project is to improve current models' ability to model the population dynamics of sea lice within areas with sharp fluctuations in daily salinity.

Background and Justification

Marine diseases and parasites have significant effects on population dynamics, consequences on life-stage structures, ecosystem functions, and when commercial species are involved, economic profit. Sea lice *Lepeophtheirus salmonis* and *Caligus spp.* are species of parasitic copepods in the family Caligidae that cause outbreaks of diseases in marine salmonids (Brewer-Dalton, Page, Chandler, & Ratsimandresy, n.d.). The economic impact associated with diseases spread by sea lice in the major marine salmonid aquaculture countries (Norway, Chile,

Scotland, Ireland and Canada) exceeds $130 million CAD every year (Brewer-Dalton et al., n.d.; Stewart C Johnson, Treasurer, Bravo, & Nagasawa, 2004). The significant costs associated with sea lice include the expense of pesticide treatment, reduced fish growth, and increased losses due to mortality (Stewart C Johnson et al., 2004; Rittenhouse et al., 2016). Parasitic lice consume mucus, epidermis skin layer and blood of host fish, reducing health and increasing morality at high lice density (Frazer, Morton, & Krkosˇek, 2012). Proper management of sea lice populations would reduce profit loss by limiting the number of treatments required, increasing the overall health of farmed fish, and increasing public opinion of aquaculture (Brewer-Dalton et al., n.d.; Stewart C Johnson et al., 2004; Rittenhouse et al., 2016).

Atlantic salmon *Salmo salar* are highly susceptible to sea lice relative to other salmonid species, due to a lack of tissue response and inflammation of epidermis skin (Gallardi, Xue, Hamoutene, Lush, & Rise, 2019). Sea lice, while found on wild salmon, occur at higher densities on farmed salmon (Frazer et al., 2012; Saksida, Bricknell, Robinson, & Jones, 2015), with one study finding that farmed stocks had higher densities compared to wild Atlantic salmon (Glover, Hamre, Skaala, & Nilsen, 2004; Holm et al., 2015). This is likely due to farmed salmon occurring at higher densities compared to in the wild, increasing sea lice's ability to breed and find suitable hosts. The levels of susceptibility of *L. salmonis* between strains of wild and farmed Atlantic salmon vary (Gallardi et al., 2019; Holm et al., 2015). Sea lice have the potential to migrate between aquaculture sites (farm-farm), as well as from farm salmon to wild salmon, and vice versa, via ocean currents (Frazer et al., 2012; Gallardi et al., 2019). Since marine-based aquaculture is open to the surrounding waters, control of sea lice spread in and out of the farms is not practical. Instead, proper pest management strategies, optimizing the start of the marine phase of aquaculture, and improved knowledge of sea lice dynamics at sites are required.

There is currently a wide range of pesticide treatments available to control sea lice densities ranging from medical baths, infeed pellets, and feeder fish (Jensen, Provan, Larssen, Bron, & Obach, 2015; Martell et al., 2013; Rae, 2002). Despite the form of sea lice control, treatments can adversely impact the health of the farmed salmon and surrounding ecosystems (Gautam, Vanderstichel, Boerlage, Revie, & Hammell, 2017). Increasing resistance of sea lice to different forms of pesticide treatment and limited regulatory approved alternatives indicates that a better solution is needed. Improved modeling of sea lice dynamics would improve management practices by providing more information about the underlying sea lice population.

There is a direct relationship between environmental conditions and life-history characteristics when it comes to the population dynamics of sea lice (Byrne et al., 2018; Groner, McEwan, Rees, Gettinby, & Revie, 2016; Hurford et al., 2019; Rittenhouse et al., 2016). Differences in temperature and salinity are critical drivers in regional population fluctuations of sea lice (Byrne et al., 2018; Groner et al., 2016; Hairston & Bohonak, 1998; Hurford et al., 2019; Rittenhouse et al., 2016), and different life stages respond differently to variation in temperature and salinity (Byrne et al., 2018; Groner et al., 2016; Hurford et al., 2019; Rittenhouse et al., 2016). Length of development time through life stages, the fecundity of adult females, and mortality are all known to be temperature dependent (Byrne et al., 2018; Groner et al., 2016; Hurford et al., 2019; Rittenhouse et al., 2016). Salinity plays a more significant role in the mortality rates of the life stages, attachment rates of successful adults, and egg development (Byrne et al., 2018; Hurford et al., 2019). Juvenile sea lice are unable to perform osmoregulation, causing them to be more susceptible to low salinities (Andrews & Horsberg, 2020; Groner et al., 2016). A lab study found that juveniles died almost instantly in low salinities (Groner et al., 2016), while adults could live up to six days in fresh water (Groner et al., 2016; Heuch, Knutsen, Knutsen, & Schram, 2002);

however, most died within 48 hours (Groner et al., 2016; Heuch et al., 2002). Rapid changes in salinity levels over short time scales may lead to rapid mortality in population structure.

Sea lice can exist in four different life stages (Frazer et al., 2012; Groner et al., 2016; Hurford et al., 2019; S. C. Johnson & Albright, 1991; Rittenhouse et al., 2016; Sandlund et al., 2018; Stien, Bjørn, Heuch, & Elston, 2005), and are assumed to be within one of four stages: nauplii, copepodids, chaimi and pre-adult/adult (Frazer et al., 2012; Groner et al., 2016; Hurford et al., 2019; S. C. Johnson & Albright, 1991; Rittenhouse et al., 2016; Sandlund et al., 2018; Stien et al., 2005). Adult females are the only stage able to produce individuals that will enter the nauplii stage via egg production. Nauplius is a broad term that refers to all planktonic non-infectious stages. Together nauplii and copepods are referred to as "larvae," while chaimi and adults are referred to as "parasites." Life stages are distinguishable by different fecundity, maturation, and mortality rates (Frazer et al., 2012; Groner et al., 2016; Hurford et al., 2019; Rittenhouse et al., 2016; Sandlund et al., 2018; Stien et al., 2005).

Goals and Objectives

The goal of this thesis is to build a non-autonomous ordinary differential equation for the sea lice, *Lepeophtheirus salmonis,* with both temperature and salinity-dependent stage durations that can adequately model the population dynamics within Newfoundland and Labrador waters. Sea lice life history is both temperature and salinity dependent, and several models have been able to predict sea lice population. Nevertheless, areas with strong daily fluctuation in salinity can still be a problem. Thus, this thesis hopes to 1) improve modelling sea lice populations within Newfoundland and Labrador waters and other locations with strong daily fluctuations in salinity levels, and 2) add to the current literature on modeling daily fluctuation in salinity.

I hypothesize that the addition of a parameter that can handle daily fluctuations will result in an R_0 that better represents the population dynamics and mimics the true value. It is unsure if the addition of this term will affect the model's ability to model sites without strong fluctuations.

Methods

Model

This study will improve upon the Rittenhouse *et al.* model, which considers seasonal variation in temperature and salinity, but is simple enough to provide the critical stock density and life stage durations(Hurford et al., 2019; Rittenhouse et al., 2016). I will be improving upon this model but adding a parameter(s) to improve the model's ability to handle sharp daily fluctuations in salinity. Rittenhouse *et al.*'s model also provides a calculation for the basic reproduction ratio, R_0, which is the number of second-generation adult females produced by a single average adult female during her life (Hurford et al., 2019; Rittenhouse et al., 2016). A study by Hurford *et al.* proved that,

Theorem 1.1(Hurford et al., 2019)

    i)   *If R_o <1 then the system is stable, and the population will go extinct*

    ii)   *If R_0 >1 then the system is unstable, and the population will continue to grow*

This theorem allows R_o to be a predictor variable for whether a specific site will increase or decline, eventually leading to extinction. When R_0 is greater than 1, the population equilibrium equation is unstable, and the population will grow year to year. When R_0 is less than 1, the population equilibrium equation is stable, and the population will decrease year to year.

The model used within this study is mechanistic of design and assumes that complex systems can be studied by examining the individual components (Otto & Day, 2007). Mechanistic

models are separated into two categories: Deterministic, which assumes that future events are entirely predictable by the model and stochastic, which assumes random or stochastic events affect biological systems, and predict the probability of various outcomes (Luger & Stubblefield, 1998; Otto & Day, 2007). Several components comprise this model; temperature is following a seasonal trend, while salinity is stochastic. Therefore, this is a mechanistic stochastic model, allowing for known information about the different components of the system to influence the biological system within the model (Luger & Stubblefield, 1998; Otto & Day, 2007).

Data from laboratory experiments for *Lepeophtherius salmonis* are used to estimate life-history parameters that are functions of temperature and salinity. Hurford *et al.* estimated the density of fish at site, *f*, and the copepodid attachment rate, *l*, using data from aquaculture sites in British Columbia(Hurford et al., 2019). Temperature, *T(t)*, and salinity, *S(t)*, will be site-specific, and all other parameters will be the same across sites.

Several parameters have been outlined within this project proposal and are summarized in Table 1.

Table 1:Name and symbols for all parameters outlined within the project proposal.

Parameter	Symbol
Nauplii	*P(t)*
Copepodids	*I(t)*
Chalimus and preadult	*C(t)*
Adult females	*A(t)*
Maturation rate	γ_i
Mortality rate	δ_i
Temperature	*T(t)*

Salinity	$S(t)$
Basic reproduction ratio	R_0

Model Assumptions

Sea lice are assumed to be within one of four stages: nauplii (P), copepodids (I) chalimus, pre-adult (C) and adult females (A). Sea lice are only able to enter a life stage through maturation or the hatching of an egg and are only able to leave a life stage either through maturation or mortality. Maturation rate (γ_i) and mortality rate (δ_i) are temperature, $T(t)$, and salinity, $S(t)$, dependent, and therefore, functions of temperature and salinity. Maturation and mortality rates vary between life-stages, and are not constant rates. Nauplii and copepodids are collectively referred to as larva, and the larval abundance at any given time are calculated by $P(t) + I(t)$. Chalimus/pre-adult, adult females and adult males are collectively referred to as parasitic and are calculated by $C(t) + 2A(t)$. See Table 1 above for complete outline parameters and symbols associated.

The model for this study will not consider any negative density dependence of sea lice on each other. On aquaculture sites, treatments are used to reduce the number of sea lice before their densities are large enough to decrease fecundity or affect survival rates (Hurford et al., 2019; Rittenhouse et al., 2016). The number of adult female sea lice per fish needed for treatment to be used varies regionally, but can be as low as one or two lice per fish (Groner et al., 2016; Hurford et al., 2019; Rittenhouse et al., 2016); although, numbers up to 20 adult female lice per fish have been recorded, suggesting that treatments tend to take place while sea lice densities are low (Groner et al., 2016; Hurford et al., 2019; Rittenhouse et al., 2016). The model also assumes that

temperature and salinity data for future years will mimic temperature and salinities from previous years.

The salmon farms sites used will be those of Newfoundland and Labrador, along with others that have large fluctuations in daily salinity. Sites will only be considered if they have complete salinity data. If any additional sites are located in the Southern Hemisphere, the temperature data will be shifted 182.5 days to allow for comparisons with the Northern Hemisphere.

This model follows the principle of parsimony and assumes that the model containing fewer variables and parameters and provides the simplest explanation is the best model (Otto & Day, 2007).

Potential Results

It is predicted that the R_0 calculated for the Newfoundland sites used by Hurford et al.'s 2019 study will now be greater than 1, indicating that the extinction equilibrium equitation is unstable, and the population will increase year to year (Figure 1) (Hurford et al., 2019). If the R_0

is less than one, this indicates that the extinction equilibrium equation is stable, and the population

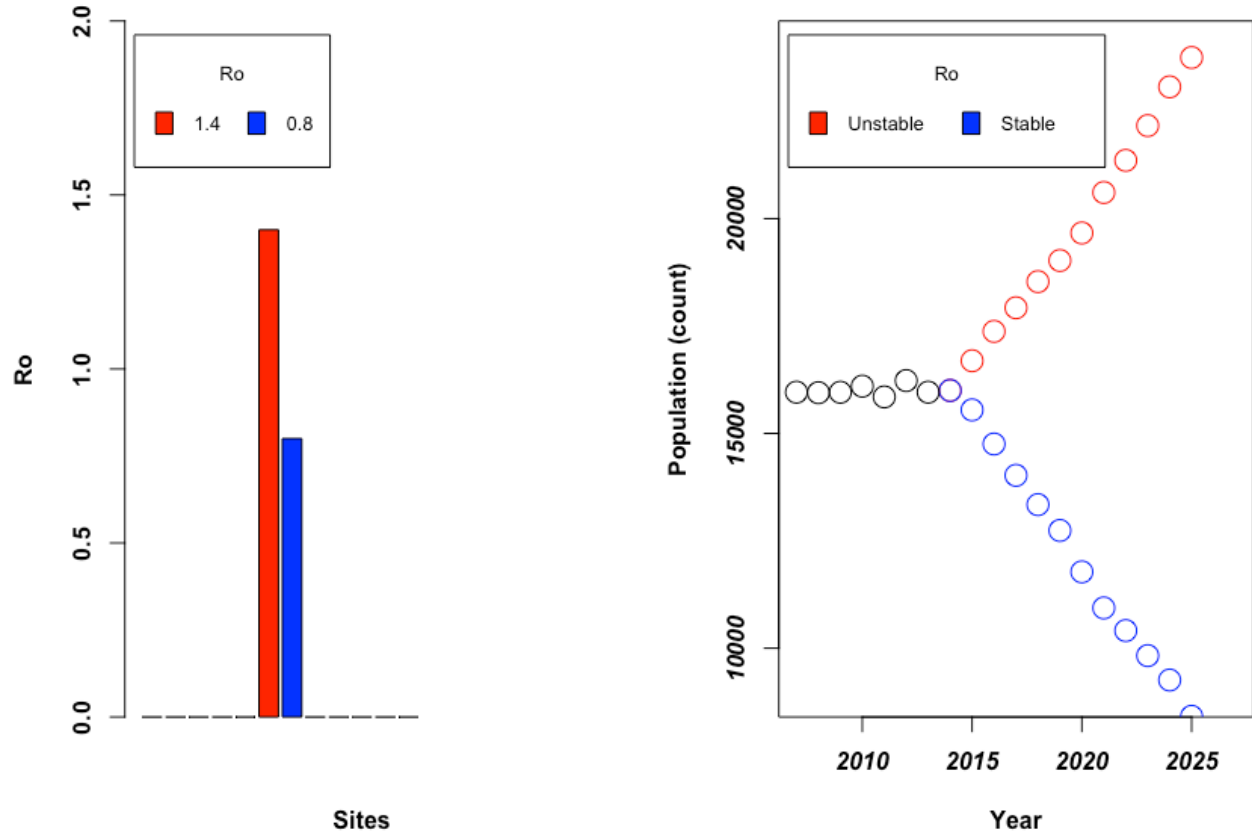will decrease year to year (Figure 1).

Figure 1: R_0 values for two possible sites indicating both sea lice population with unstable equilibrium equations and growing population ($R_0 > 1$) and stable equilibrium equations and decreasing populations ($R_0 < 1$). Red points represent a site with a R_0 greater than 1, and an unstable equation indicating that the population will grow. Blue points represent a site with R_0 less than 1, and a stable equation indicating that the population will decrease, leading to extinction. Data used does not represent physical sites.

The salinity levels at Newfoundland and Labrador and other sites used in this study are

expected to have a higher difference between the maximum and minimum daily salinity levels.

Additionally, the seasonal maximum and minimum salinity levels will vary compared to other

sites; however, the direction of the difference is unknown. One possible outcome is that the seasonal maximum and minimum will be less than the control site (Figure 2).
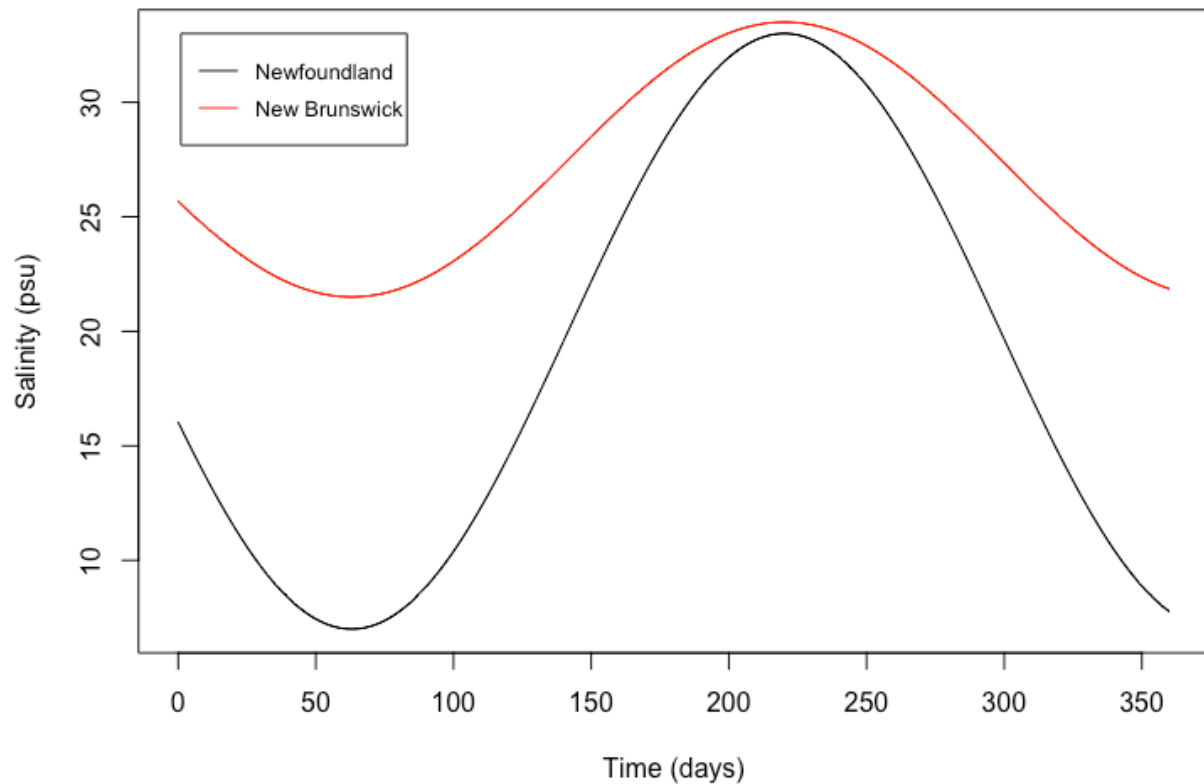

Figure 2: Predicted salinity data throughout the year. Black line represents salinity data for Newfoundland and the red line represents New Brunswick aquaculture sites. Both cultures are fabricated data and predictions of the actual trends in data. New Brunswick site is acting at the control site. Both curves are representing fabricated data.

The daily fluctuation in salinity, seen as intense noise around the curve, is expected at Newfoundland and Labrador sites. (Figure 3). Adding a parameter to improve the model's ability to handle sharp daily fluctuations is not expected to negatively affect the model's performance for sites without sharp daily fluctuations.
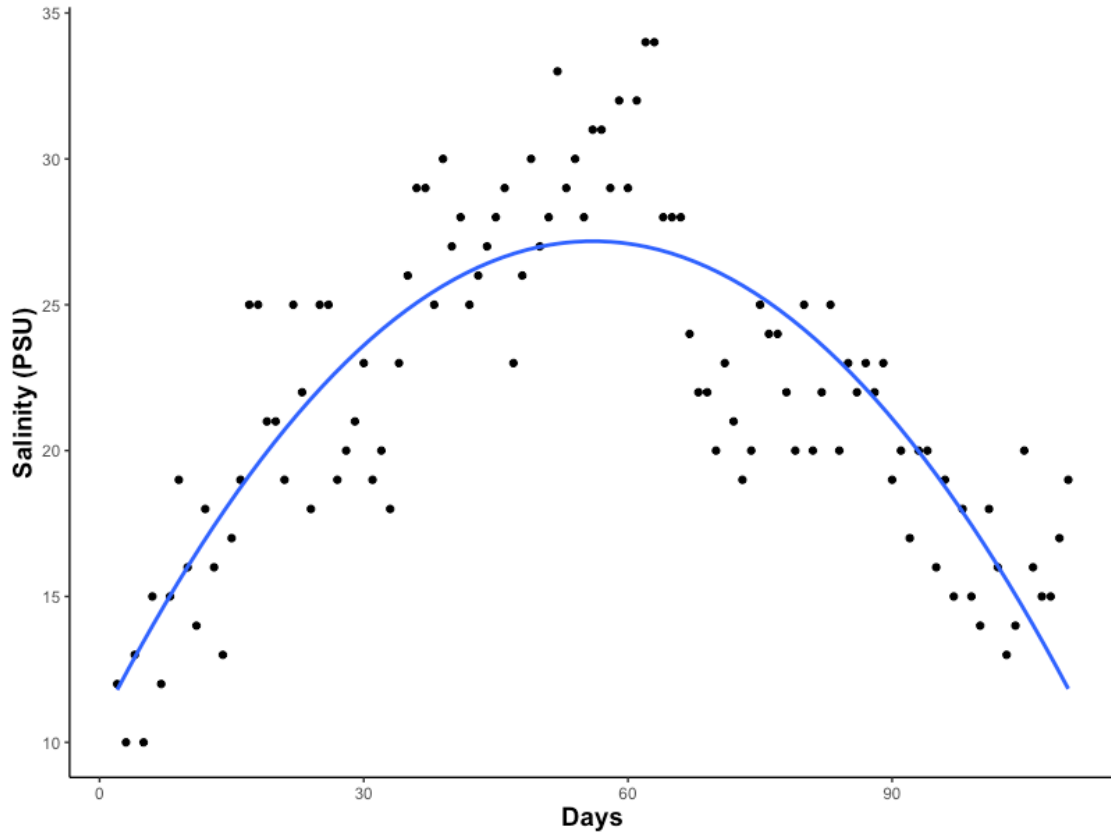
Figure 3: Salinity curve for predicted Newfoundland data showing noise (black dots) around the salinity curve. *Fabricated* salinity day from January 1st to April 20th.

It is predicted that the sea lice population will be a function of temperature and salinity. Thus, parameters that improve the understanding of temperature and salinity will improve the understanding of sea lice, allowing the model to predict the true R_0 value. Population trends over large time scales are predicted to be more sensitive to temperature, while daily changes in population are predicted to be functions of salinity.

Timetable and milestones

The project will begin in September 2019 with a literature review on sea lice, management strategies, life-history structures, and population models and will continue until the end of January

2020. During this time, I will begin my project proposal in September and present a full proposal in November 2019 to the Memorial University Biology 7000 Graduate Seminar class and again in late January 2020 to my thesis committee. I will begin building my model in October 2019 and continue until December 2020. I expect to have my first draft of my thesis completed by November 2020, where it will then be edited from November 2020 to April 2021. I will begin the submission process in April 2021. The Gantt chart below outlines the key dates of my project below (Figure 4).
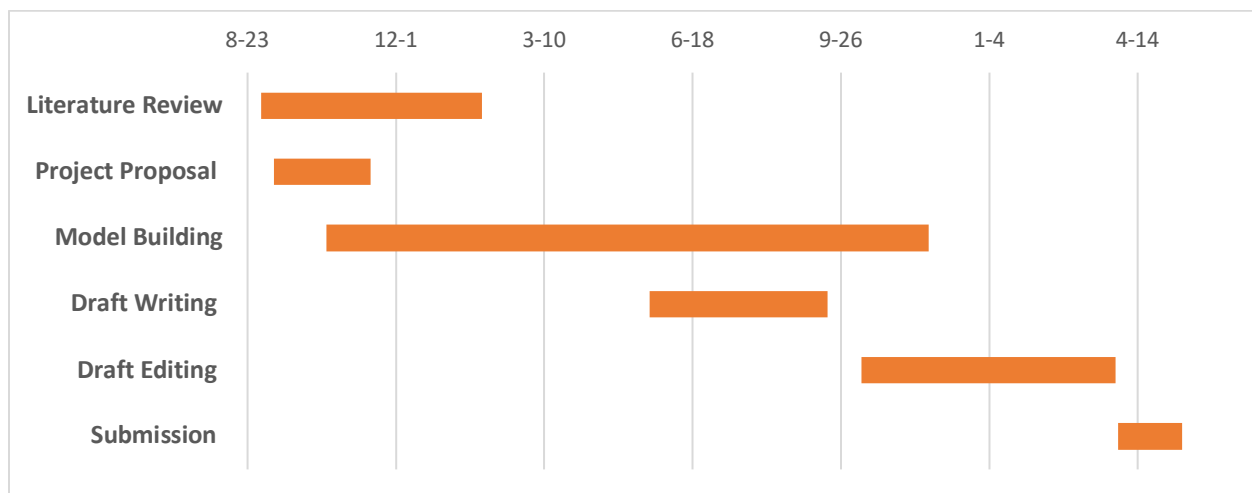
Figure 4: Proposed project timeline with the start date being September 2019 (09/01/19) and expected end date in May 2021 (05/12/21).

List of Figures and Tables

Figures

Tables

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