Spatio-Temporal Analysis of Sustainability: Lane County, Oregon.

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Introduction, Editing , Literature Search, References, Methodology, Results, Code (RStudio), numerical figures.

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1 Introduction

Water resources are already scarce in many parts of the world and "The 2018 edition of the United Nations World Water Development Report stated that nearly 6 billion peoples will suffer from clean water scarcity by 2050" (Boretti & Rosa, 2019). The Sustainability of Lane County, Oregon Capstone project will focus on the sustainability of an unconfined aquifer system within Lane County, Oregon (Figure 5) with regards to factors such as precipitation rate and population growth. The local government of the Eugene-Springfield area, the largest urbanized area within Lane County, already has sustainability practices in place for groundwater resources. A groundwater report by the USGS notes that "In recent years, withdrawal of groundwater for irrigation and industrial, domestic, and public supplies has increased progressively in the Eugene-Springfield area" (Frank, 1973). The area currently supports a variety of land cover and land use types, including but not limited to: timberland, commercial forestry, orchards, pastures, and row crops, with the most substantial amount of agricultural land centered around the Eugene-Springfield area (McCarthy et al., 2014). Each land cover type provides a unique challenge to assessing water sustainability due to how each type affects aquifer recharge. The current biodiversity of Lane County is possible only with a continued focus on unconfined aquifer system sustainability, the county's most relied upon water source. Despite the aquifer system's general ability to recharge annually noted by Frank (1973), Frank also notes the potential for future problems in the water resources due to both local overdraft of water wells and improper well construction. Water sustainability covers not only environmental factors like precipitation rate, but population forcing factors like water consumption and water well output. As a collective responsibility, the sustainability issue encompasses numerous domains of knowledge and can only be addressed with approaches that account for the complexity of earth systems hybrid nature (Badiru et al., 2021).

1.1 Project Objectives

The objectives of the project include the following:

- Understanding the water inputs of the unconfined aquifer system and population outputs that affect the unconfined aquifer system in Lane county, Oregon.
- Characterization of forcing trajectories of precipitation and population in Lane County, Oregon.
- Assessment of water sustainability and population-shelter sustainability of Lane County, Oregon.
- Formation of two management scenarios to enable decision support and provide guidance to further improve overall sustainability of Lane County, Oregon.

1.2 Project Significance

Understanding the groundwater resources and the sustainability of these resources over time can provide valuable information for government officials, as well as citizens to find ways to help preserve the natural resources of the local area. Most significantly, this project will assess the current sustainability of Lane County's groundwater resources, characterize their change over time through a written report with visualizations, and direct future urban development in the area through management scenario simulations. Completion of this project will provide a snapshot into the current and future state of water resource sustainability in Lane County.

2 Literature Review

2.1 Sustainability

The concept of sustainability is multifaceted, and context is required in order to properly approach the definition of sustainability for each unique use case. For the purposes of this spatio-temporal analysis, sustainability relates to the notion of carrying capacity of a particular environment as outlined by Daily et al. (1992). In this context, sustainability refers to the ability of the environment to support the organisms within it as the organisms themselves interact with the environment. Furthermore, sustainability as it relates to groundwater resources has been explored through the use of sustainable groundwater management indexes, which help assess the status of quantity and quality of groundwater resources. Once such assessment includes the Drivers, Pressures, State, Impact and Response Model (DPSIR) intervention model framework, which incorporates factors that affect aquifer sustainability over time. This DPSIR model includes 5 indexes to characterize various aspects of the study area's level of sustainability, including but not limited to: social, economic, physical, biological, chemical, and change (Samani, 2021). The study of Lane County mirrors this sustainability index approach with its weighted evaluation of groundwater sustainability that accounts for population and precipitation forcing factors, however, this project differs significantly in scope and will not include factors such as economic and social interactions within the population. The overall sustainability for the study area appears positive for both factors, especially considering rainfall averaged less than an inch higher than current results in the 1970s and the population of Lane County has not grown significantly since then (Frank, 1973). This is one reason why this sustainability analysis is novel, since the Lane County community is comfortable with their current environmental conditions and academia has not yet explored land cover management scenarios for negative environmental outcomes that are possible in the future for this particular area.

2.2 Population Growth and Sustainability

The world's population plays a huge role in the sustainability of our planet. The use of water resources per person varies drastically from place to place, with the bare minimum for survival being between fifteen to twenty liters (Singh et al., 2014). In the United States, the daily water usage averages 575 liters, while in Phoenix, Arizona, it averages about a thousand liters per person, mostly used on watering the lawn (Singh et al., 2014). As the population continues to grow, those average per person usage numbers might stay the same, but there will be more people requiring that level of water daily. If water resource sustainability is not increased, the population will eventually hit the carrying capacity for water resources, and become completely unsustainable. Not only does water consumption grow with a growing population, land use and living space for the population also has to be considered. As urban sprawl increases, water infiltration and recharge get reduced, as water cannot infiltrate through urban surfaces like concrete and asphalt as easily as soil and other natural surfaces (Romero and Ordenes, 2004). In a study of urban sprawl in Iran, "urban sprawl is said to represent a threat for urban sustainable development since it implies an increase in the consumption of land, water, energy and other resources as well as of pollutants and waste" (Mohammadi et al., 2012). In order to ensure that the groundwater in the study area for research can be sustainable over time, urban sprawl must be considered, and a possible management scenario is increasing urban density instead of allowing for low density urban sprawl in the area, allowing for more recharge areas.

2.3 Groundwater Resources and Sustainability

Groundwater resources play an important role in freshwater resources all around the world. A study on groundwater sustainability in Morocco by Ahmed et al. (2021) found that there was an immediate need for more policies being created to keep the water resources in the area from being exploited and polluted. As the population grows, the need for freshwater resources will also grow. In a study completed in India by Islam et al. (2021) on groundwater variability and sustainability, it was discussed that as the population continues to increase, the strain put on India's groundwater resources will only get worse unless drastic changes are implemented. Islam et al. also stated that Indian agriculure's water usage is approximately 70% groundwater, so major depletion of groundwater could result in food scarcity as well as water scarcity. Although in this study of Oregon groundwater recharge is only being modeled by precipitation rates, other studies have also included mountain side runoff, river infiltration, and irrigation return as other forms of groundwater recharge (Qin, 2021). Other types of recharge are important to account for, but in general, precipitation infiltration is the bulk of groundwater recharge. Each of the studies above focused on spatio-temporal analysis given past data, however, none calculated nor predicted future groundwater resources based on the past results and trends. It is important to understand the current state of our resources, but it is also equally, if not more important, to examine how the trends over time will carry into the future. More robust management solutions could be created if one has a prediction of what the future might look like in terms of groundwater resource sustainability.

2.4 Spatio-Temporal Analysis

A key goal of Spatio-Temporal analysis is properly characterizing both the spatial and temporal dimensions. An aspect of this spatio-temporal analysis is forecasting future precipitation over a 50 year period based on historical data, with one weather station in Eugene, Oregon selected for this model. However, a stochastic rainfall study done by Baigorria et al. (2010) argues that one weather station is not enough to properly spatially characterize precipitation, hence the attempt to create a stochastic model for daily rainfall over numerous weather stations for an inclusive spatio-temporal analysis of a given area. In contrast to the current trajectory of spatio-temporal analysis studies like Baigorria et al. (2010) and McCarthy et al. (2007) attempts to better spatial distribution of environmental phenomena over large areas, the Lane County project only includes precipitation data from one weather station. Despite this, the temporal aspect of the study follows the academic trend that in order to characterize an area fully, the temporal dimension must be accounted for. A novel factor of this analysis is that the calculations were done using an iterative script in R, so simulations can be run repeatedly with simple changes to individual variables that automatically create new visualizations that characterize the output (Figure 13).

2.5 Statistical Analyses

In terms of statistical analysis for aquifer groundwater sustainability, there is a common trend of creating indexes to characterize the sustainability of an area (e.g., Aliewi et al., 2021, Bui et al., 2019, Samani, 2020). Most of these indexes have porosity coefficients built in because precipitation infiltration is affected heavily by the geology and lithology of a given area, which can greatly affect the aquifer sustainability index (Aliewi et al., 2021). Due to the increasing complexity of sustainability analysis, Bui et al. (2019) calculated the most appropriate and equal weight for each criterion in a sustainability study to reduce tedious calculations that do not bode well for comparative analysis with other studies that characterize sustainability indices in a completely different way. The Lane county study uses a weighted approach to computing this index, which is different from the equal weight approach done by Bui et al. (2019) when addressing groundwater sustainability. Because of the simplistic nature of the Lane County study, and the relatively small population of the area, a weighted approach is more appropriate for this specific case where population may not play as large a role. In addition to the sustainability indices, a large portion of evaluating the sustainability of the area is the ability to toggle land cover areas for management solutions based on an initial unsupervised ISODATA classification, which is a straightforward and popular approach to expedite land cover classification for groundwater sustainability purposes as demonstrated by Liaqat et al. (2021), which evaluated the impact of land cover on the groundwater resources in the Al Ain region of the United Arab Emirates. Although the study area where this classification was done differs from Lane County in the type of vegetation, Lane County is mostly one land cover type (forested) like the Al Ain region in the U.A.E. (mixed urban/sandy).

3 Methodology

3.1 Data

For the spatio-temporal analysis of Lane County to match the reality of the state of sustainability in Lane County, numerous forms of data were collected to build the foundational integrity of the entire project. Data that is both spatial in nature as well as temporal in nature had to be considered for a proper analysis of the area over a 50 year time period (Baigorria et al., 2010). Precipitation data was collected from the CocoRaHs Water Year Summary Reports Weather Station Eugene 2.7 (OR-LA-112) for the years 2000-2021 (CoCoRaHS, 2021). For population data, the US Census was used to collect population by year from 2010-2019 (US Census, 2019). The (x,y) location of each well within Lane County was collected from the Oregon Water Resources Well Report (OWRD, 2021). Aerial imagery of Lane County was provided by LandSat 8 from the USGS Global Visualization Viewer (GloVis) (USGS, 2021). Lastly, six DEMs at ⅓ arcsecond resolution that encompassed Lane County were collected from the USGS National Elevation Database (USGS NED, 2021).

3.2 Climate and Population Forcing

In order to properly characterize the systems in Lane County, the inputs and outputs of the system were accounted for through characterization of forcing factors like precipitation and population. First, the basic precipitation input into the system for this study was represented as:

$$P_i(t) = P_0 + \beta_1 t, \tag{1}$$

which accounts for both the base precipitation rate, P_0 (the mean precipitation), and the linear slope coefficient, β_1 from the precipitation trend over 13 years, multiplied by time to account for the change in precipitation over time. Precipitation was the main method of unconfined aquifer recharge for this study (Figure 4).

The next main forcing factor characterized was the population of Lane County, which both benefits from and affects sustainability of the area. The rate of population growth within the system plays an important role in sustainability analysis because as the population grows, the more space and water will be used. The computation for the population growth rate is:

$$p(t) = p_0 exp^{(kt)}, \tag{1-1}$$

where p_0 represents the base population at year 0, or the starting year for the simulation. This base value is multiplied by the exponential raised to time, t, multiplied by the growth rate coefficient, k.

3.3 Land Cover Classification and Recharge

Using two Landsat 8 images from GloVis, a land cover classification for the study area was created using ArcGIS Pro's IsoCluster algorithm (Figure 1). In order to assess the accuracy of this classification, the output was compared to the National Land Cover Database's classification image of the area, while also checking it against the aerial imagery itself. The recharge zones were created by reclassifying the land cover raster with a fraction of recharge (Figure 3), where areas of high infiltration, like bare soil, received values that are closer to one, while areas of lower infiltration, like concrete, received values closer to zero (Romero and Ordenes, 2004). Then this reclassified raster was combined with a slope map (Figure 2), which was created using DEMs of the Lane County area. Locations that have higher slopes have a lesser recharge rate, while lower slopes have a greater recharge rate. These rasters are then multiplied together to yield a complete recharge map.

3.4 System Characterization and Modeling

Next, calculating the porosity corrected depth of water was completed using the equation:

$$H\_p\ (t) = (H\_w\ (t))/\Phi\_p \ , \tag{2}$$

which involved the actual depth of the water table over the study area(which accounted for precipitation and planimetric area of the entire study area) as a function of time divided by the chosen unconfined aquifer porosity coefficient, Φ_p, of 0.3, changed from the initial 0.45 because Lane County aquifers have particularly low porosity compared to other aquifers (Conlon et al., 2016). The water table, as a function of future time represented as:

$$Z_w(t + 1) = Z_w(t) + H_p(t), \tag{2-1}$$

was calculated next, where the water table height, $Z_w(t)$, was combined with the porosity corrected height/depth of water, $H_p(t)$. In order to calculate the number of people that can be sustained by an increase in residential area, the equation

$$N_p(t + 1) = \frac{{N_p}^o}{R}, \tag{2-2}$$

was used, which represents the area of a residential space that can hold six people, N_p^0, divided by the increase of residential area to accommodate a growing population, R. Modeling the water table height over time accounts for the depth water input from precipitation, $H_p^I(t)$, and subtracts the depth of well water output based on the amount of water pulled from wells in the area calculated as:

$$Z_w(t)+ = H_p^I(t) - H_p^0(t), \tag{2-3}$$

Standardization of these parameterization schemes for this project is key in order to efficiently adjust model variables in the event of differing sustainability outcomes, and consequently model different management scenarios for Lane County.

3.5 Calibration and Sustainability Metrics

Assessing the groundwater sustainability of Lane County requires both the sustainability of the growing population over time, and the sustainability of groundwater over time. The equation to calculate the sustainability index for groundwater is:

$$S_w(t) = \frac{V(t) - V_w^{\,0}}{V(t) + V_w^{\,0}}, \tag{3}$$

where first the base volume of water must be calculated, (V_w^0) and the volume at time *t*, V(t), is calculated using the volume of water at the time, the volume from the year previous, and the amount of water being removed from wells.

The sustainability index for population and the area needed to house them is calculated using:

$$S_p(t) = \frac{A_s(t) - A'(t)}{A_s(t) + A'(t)}; \tag{3-1}$$

a ratio of the area designated for human shelter, As(t), and the area required for the population increase, A'(t).

The results from the above sustainability indices are combined in an overall weighted sustainability represented as

$$S = \frac{w_1 S_w + w_2 S_p}{w_1 + w_2}. \tag{3-2}$$

The two indices above are multiplied by a weight relative to their perceived importance on overall sustainability and divided by the sum of those weights to produce a measure of overall sustainability, with respect to the two main forcing factors studied. Similar indices were created by Bui et al. (2019) except with equal weights for each index, in contrast to this project's approach of differing weights by importance for the indices, where water sustainability was rated as twice as important as population, as the study area has very little population compared to the habitable area.

3.6 Management Scenarios and Initial Conditions

Because urban sprawl plays a major factor in land cover change, management scenarios that relate to limiting urban sprawl are mostly considered. When considering urban sprawl in many countries, Habibi & Asadi (2011) found that consolidating urban areas is a good solution. Urban consolidation prescribes using areas that are already built up more effectively. Examples could be redeveloping old neighborhoods into more high-density housing or utilizing previously abandoned locations into more space for the city to develop. In addition to infrastructure changes to improve existing areas, land cover can be changed in undeveloped areas to better support the population. Since sustainability depends on the ability of the environment to support the organisms within it, changing the land cover to be less dense in vegetation to support easier recharge of the aquifer could increase water reserves in the area to support an inevitable increase in population (Daily et al., 1992). The management scenarios consider a negative outcome for sustainability of Lane County. In the event of a positive sustainability outcome, management scenarios will focus on reinforcing existing conservation protocols, such as limits on well water use and continued enforcement of sustainable agricultural practices for the area.

Initial conditions for adjustable variables for calibration of the Default Scenario are displayed in Table 2. All simulations of management scenarios were done in RStudio using a script that iterated over the 50-year period (Figure 13).

4 Results

4.1 Default Simulation Results

Initial conditions (Table 2) had an overall positive sustainability index of 0.2676 for the first 10 years before the index illustrated negative sustainability, reaching a low of -0.2238 at year 50 (Figure 12). This was due in part to the water sustainability index rising to 0.02659 at 30 years before falling to 0.01372, but mainly as a consequence of the population-shelter index falling sharply at the 10-year mark to highly unsustainable levels with an end index of -0.6863 (Figure 10). Initial conditions set for water and population-shelter were overall unstainable for Lane County.

4.2 Management Scenarios 1 and 2

Because the initial simulations with default conditions were unsustainable, the management scenarios created focused on improving sustainability of Lane County, OR for the residents: Management Scenario 1, “Population-Shelter Management Scenario”, involved changing only population-shelter metrics, while Management Scenario 2, “Water and Population-Shelter Management Scenario”, involved changing both water and population-shelter metrics.

4.2.1 Population-Shelter Management Scenario

Management Scenario 1, the “Population-Shelter Management Scenario” conditions (Table 3) made Lane County more sustainable by only changing population-shelter variables (k, People per Residence, Shelter Increase) in the default simulation. This lowered population growth (Figure 6) and lowered the amount of shelter required to house the growing population (Figure 7). The resulting Population-Shelter Index improved dramatically, going from an unsustainable -0.6863 at 50 years to a completely sustainable 0.3006 at the 50-year mark (Figure 10). This changed the overall sustainability index from the default -0.2238 to a positive combined sustainability index of 0.1093 at the 50-year mark.

4.2.2 Water and Population-Shelter Management Scenario

Management Scenario 2, the "Water and Population-Shelter Management Scenario" was the most effective simulation for increasing overall sustainability of Lane County. In addition to the population-shelter variables altered in Management Scenario 1 (k, People per Residence, Shelter Increase) the water well output was also changed from 100% to 80% (Table 4). This added 0.77 m to the peak water table height, rising from 36.66 m to 37.43 m (Figure 9). This resulted in a positive increase of the Water Sustainability Index, going from the Default and Management Scenario 1 index of 0.0137 at the 50-year mark to 0.0148 (Figure 11). The overall sustainability index then increased from -0.2238 in the Default Scenario, 0.1093 in Management Scenario 1, to an end result of 0.1101 for Management Scenario 2 (Figure 12).

5 Discussion

5.1 Limitations and Assumptions

While this project strives to maintain a realistic representation of reality, some representations of reality have been simplified to fit within the semester time frame and scope of the project. For example: when considering recharge areas, all water that fell on impervious surfaces such as roads or residential areas was considered lost water, so runoff from impervious surfaces was not considered in the calculations. Also, the precipitation rate used for the project was from one weather station in the Eugene-Springfield area, as that was the only precipitation information available. The assumption was made that precipitation was homogenous throughout the entire county area. The Porosity of 0.3 for the unconfined aquifer system was based on data from Conlon et al. (2016), and it was assumed that the entire aquifer system had the same porosity.

5.2 Local population growth and precipitation patterns

In many places, the constant large population growth in cities tends to cause many issues for water sustainability and availability for residents. In the UAE, the current projections of population growth mean that there will not be enough freshwater supply by 2030 (Giwa & Dindi, 2017). The population in Lane County, while it is growing in a positive direction, has a much less dramatic increase in the next fifty years, as the area is more rural, so there is less migration to the area than major cities. However, there is still a need for water conservation to promote sustainability, as projections have shown that the study area's precipitation rate will decrease throughout the next fifty years (Figure 8). Because of this precipitation decrease, a potential change to the overall weighted sustainability index might be to increase the significance of water sustainability from the chosen weight of 2, as it is the more pressing issue in terms of sustainability.

6 Conclusions

Understanding groundwater sustainability over space and time is a hugely important area of this study as the climate continues to change and population continues to grow. Using numerical modeling concepts and parameterization schemes to represent reality was the main focus of this project. Once the sustainability of the study area was calculated with the initial default conditions, it was discovered that Lane County was unsustainable overall (Figure 12). The main reason for this was the combination of exponential population growth and the general precipitation trend decreasing throughout the 50 year time period. With these results in mind, two management scenarios were created to discover whether a few changes would change the sustainability overall. Because the code (Figure 13) was created to easily change variable values between simulations, management scenario changes were easy to test and compare to the original results. The first management scenario adjusted values related solely to population and shelter metrics, as the original simulation results showed a negative population and shelter sustainability index. The policy adjustment that was tested was having more high-density housing instead of single-family residences— increasing the number of people per residence, and decreasing shelter area growth. The second management scenario was a combination of the same population sustainability adjustments in the first management scenario and changing the water well output to 80% of its potential. This management scenario was an implementation of a water usage limitation scenario, where water wells were unable to draw as much water out as their full capacity. The two management scenarios that were created were able to change the overall sustainability of the study area from negative to positive, with Management Scenario 2 being more effective at increasing overall sustainability than Management Scenario 1 (Figure 12).

In order to create a more detailed representation of reality for future work, more spatial variability of features would increase the accuracy and completeness of results for each area. Since many things like precipitation, soil porosity, and population were assumed to be uniformly spread throughout the study area, this creates more generalized results for the Lane County as a whole. Also, the fact that ocean water could be desalinated and used as a water source was left out of the project scope, and this could change the results as well. Other management scenarios such as water use limitations for lawns, reducing forest cover for more bare soil, and decreased agricultural use would also be important to investigate for future work. However, this project's generalization of current results allows for a more inclusive and county-wide view of sustainability over time, which is ideal for creating legislation to increase overall sustainability.

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8 Tables

Table 1: All variables used in the sustainability modeling with definitions and units.

Variable	Definition
P_0	Base Precipitation Rate [m-yr^{-1}]
β_1	Slope Coefficient of the Linear Trend
t	Time [yr]
$P_i(t)$	Precipitation Rate [m-yr^{-1}]
z_{min}	Minimum height in study area [m]
z_{max}	Maximum height in study area [m]
Z_w	Water Table Altitude [m]
Z_b	Unconfined Aquifer Base [m]
Φ_p	Unconfined Aquifer Porosity [dimensionless]
V_w^0	Base Volume of Water for Geographic Area [m^3]
LW	Constants that represent width of cell [dimensionless]
V_w	Total Precipitation Water Volume [m^3]
H_w	Height of precipitation [m]
A_p	Planimetric area of study area [m^2]
H_p	Porosity-Corrected Height of Precipitation [m]
k	Population growth coefficient [dimensionless]
A_r^b	Residential Requirement per Residence [m^2]
N_p^0	Number of People per Residence [dimensionless]
$A_r(t+1)$	Shelter Increase per Residence [m^2]
R	Ratio of Residential Requirement to Shelter Increase [dimensionless]
$N_p(t+1)$	Number of People Accommodated by Shelter Increase

W_p	Daily water consumption for 1 person [m^3]
Q_w^p	People Water Consumption Requirements [m^3]
Q_{well}	Water discharge per well [m^3]
N_w	Number of water wells
W_i	Water Well Coefficient [dimensionless]
$Z_w(t)$	Water Table as a function of time [m]
$S_w(t)$	Sustainability Index for Water [dimensionless]
$S_p(t)$	Sustainability Index for Population-Shelter Requirements [dimensionless]
S	Overall Weighted Sustainability Index [dimensionless]

Table 2: Table provides the chosen defaults for time period 0 of the original sustainability of Lane County based on current implemented measures. From this point forward, the variables are adjusted to simulate a potential increase in overall sustainability.

Variable	**Defaults**
Z_b	-1012.9302 m
k	1.1
A_b^r	93 m^2
$N_p^{\boldsymbol{0}}$	6
$A_r\ (t + \boldsymbol{1})$	10 m^2- yr
W_p	5 m^3- day
N_w	250000/36 (6944.445)
W_i	1 (ALL)
Q_{well}	2389.43 m^3 - yr
$w_{\boldsymbol{1}}$	2
$w_{\boldsymbol{2}}$	1

Table 3: Table provides altered variables for Management Scenario 1, the "Population-Shelter Management Scenario" that only adjusted the population growth constant k, People Per Residence N_p^0, and Shelter Increase $A_r(t+1)$.

Variable	**Management Scenario 1**
Z_b	-1012.9302 m
k	0.01
A_b^r	93 m^2
N_p^0	8
$A_r\ (t+1)$	1 m^2- yr
W_p	5 m^3- day
N_w	6944
W_i	1 (ALL)
Q_{well}	2389.43 m^3 - yr
w_1	2
w_2	1

Table 4: Table provides altered variables for Management Scenario21, the "Water and Population-Shelter Management Scenario" that adjusted the population growth constant k, People Per Residence N_p^0, and Shelter Increase $A_r(t + 1)$, in addition to the changed the water well output, N_w from 100% to 80%.

Variable	**Management Scenario 2**
Z_b	-1012.9302 m
k	0.01
A_b^r	93 m^2
$N_p^{\boldsymbol{0}}$	8
$A_r\ (t + \boldsymbol{1})$	1 m^2- yr
W_p	5 m^3- day
N_w	(0.8)*(6944)
W_i	1 (ALL)
Q_{well}	2389.43 m^3 - yr
$w_{\boldsymbol{1}}$	2
$w_{\boldsymbol{2}}$	1

9. Figures

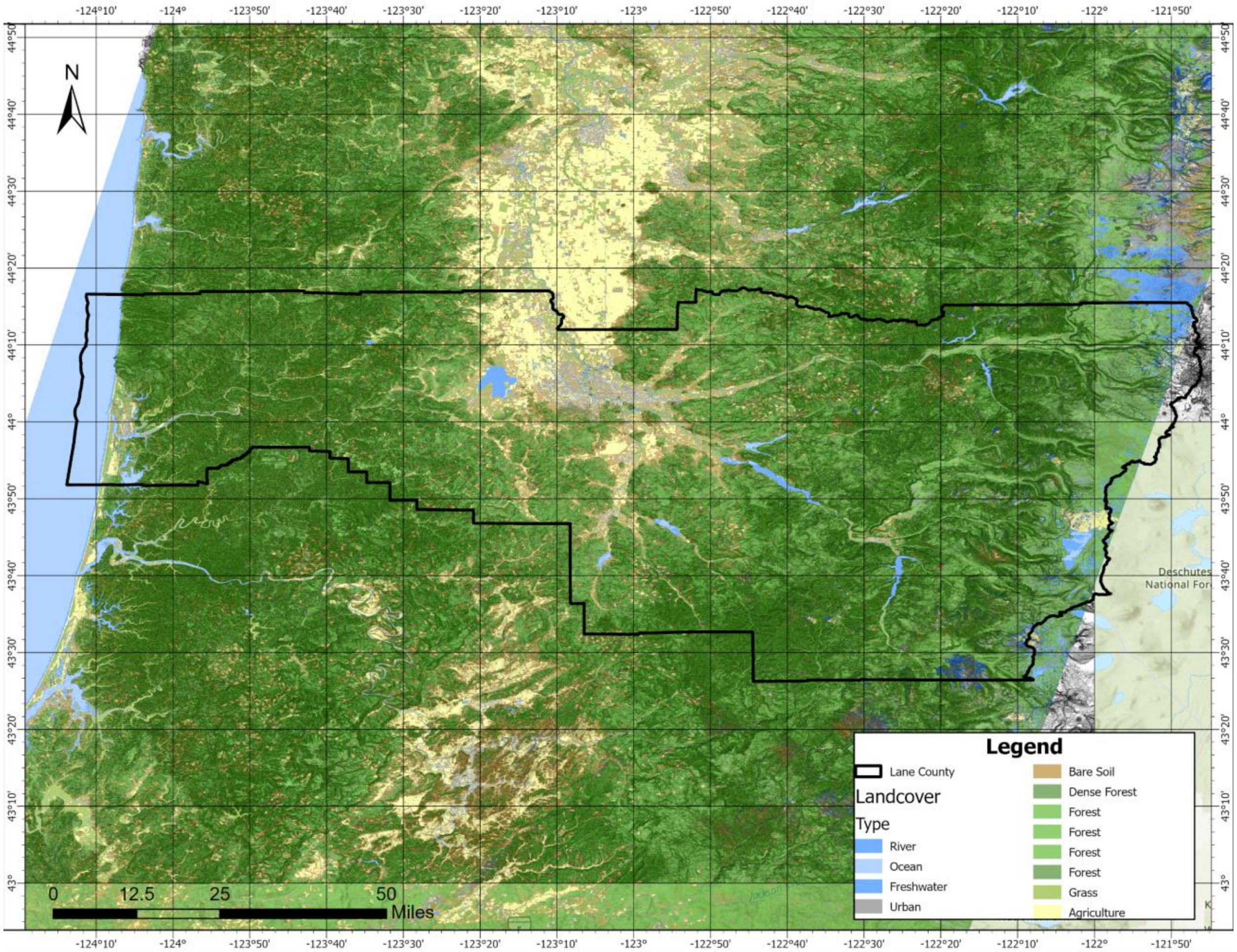


Figure 1: Landcover of Lane County laid overtop of slope maps for the region to give texture to the landcover map. Lane County is mostly forested with agricultural areas being the second highest use of landcover area. The landcover classification was created using Landsat 8 imagery from Glovis, and processed in ArcGIS Pro. The DEMs, which were calculated from DEMs, are from *TNM Download v2.*

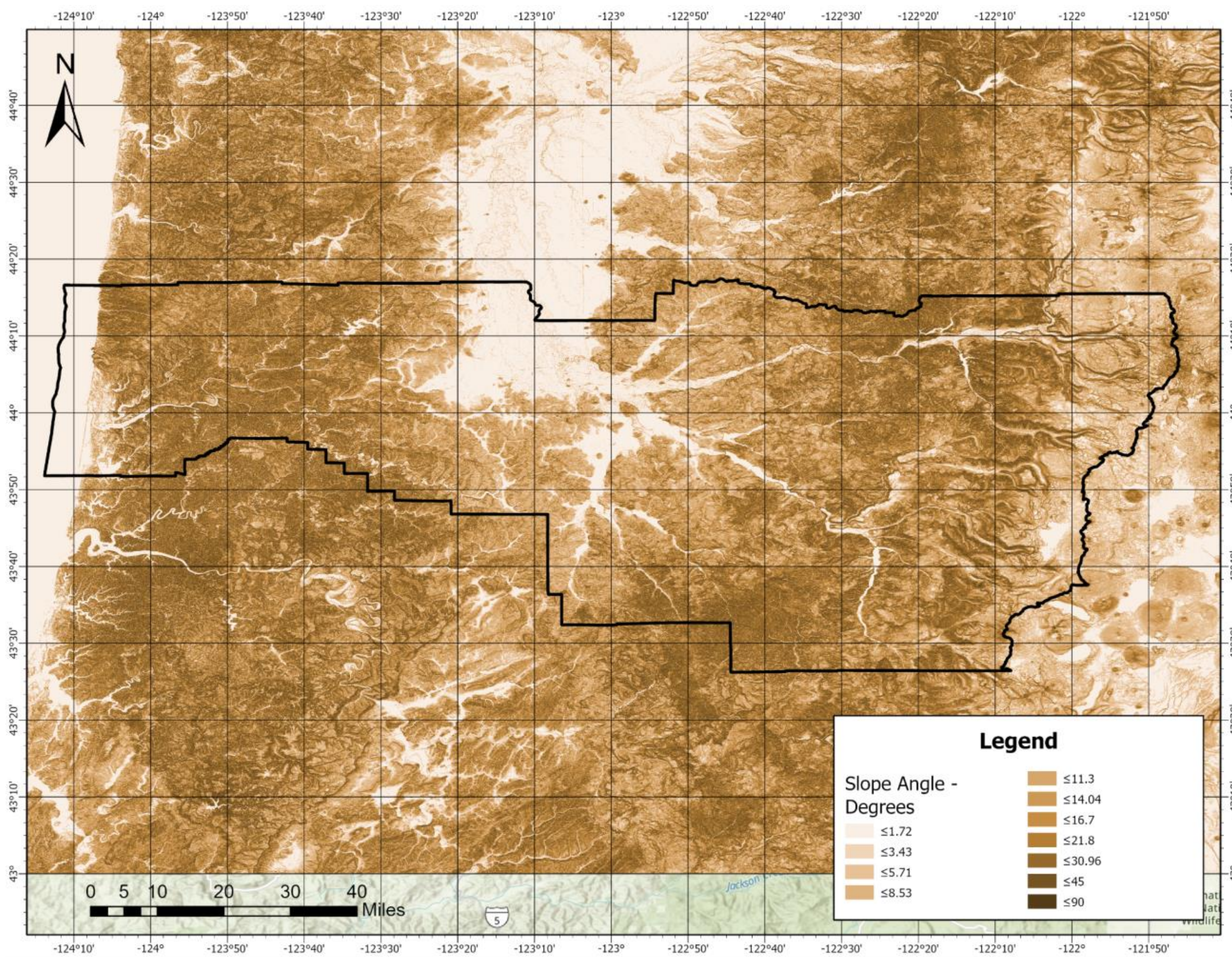


Figure 2: Slope calculations of Lane County and the surrounding regions in degrees. The slope calculator was created using eight DEMs of from *TNM Download v2*. The slope maps were created using ArcGIS Pro's slope calculator tool.

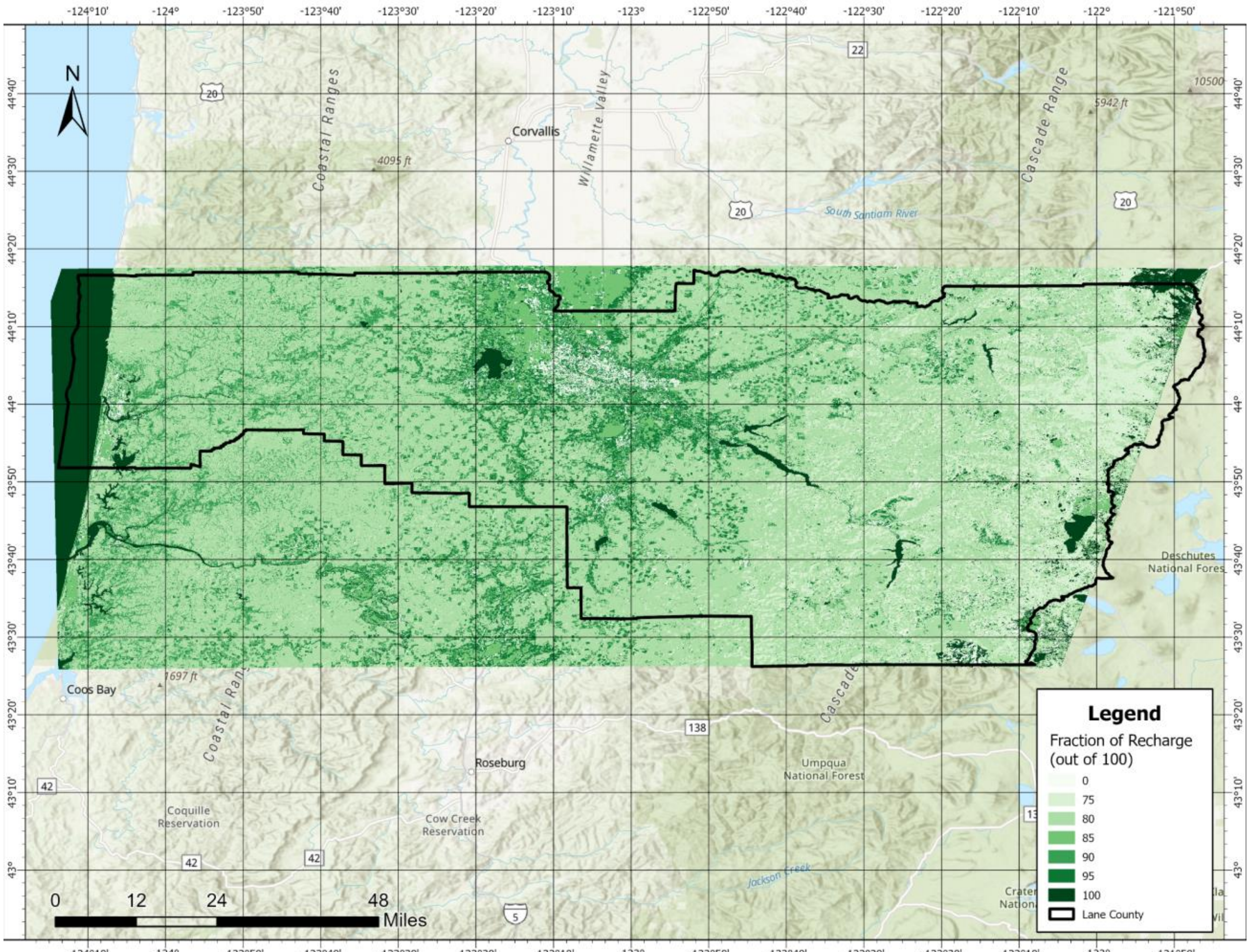


Figure 3: A map showing a reclassified version of the recharge map. Landcover types were assigned a value between 0 and 100 to demonstrate the level recharge from precipitation with reference to the landcover types. A value of 0 represents an impervious surface and residential areas, where no water will infiltrate and make it into the groundwater. Forested areas have a value of 75-85 based on how heavily forested the area appears. Agricultural areas have a value of 90 as they will allow more water to make it into the aquifer than forested areas, while bare soil has a value of 95, as there is very little vegetation to absorb the precipitation before it can make it to the aquifer.

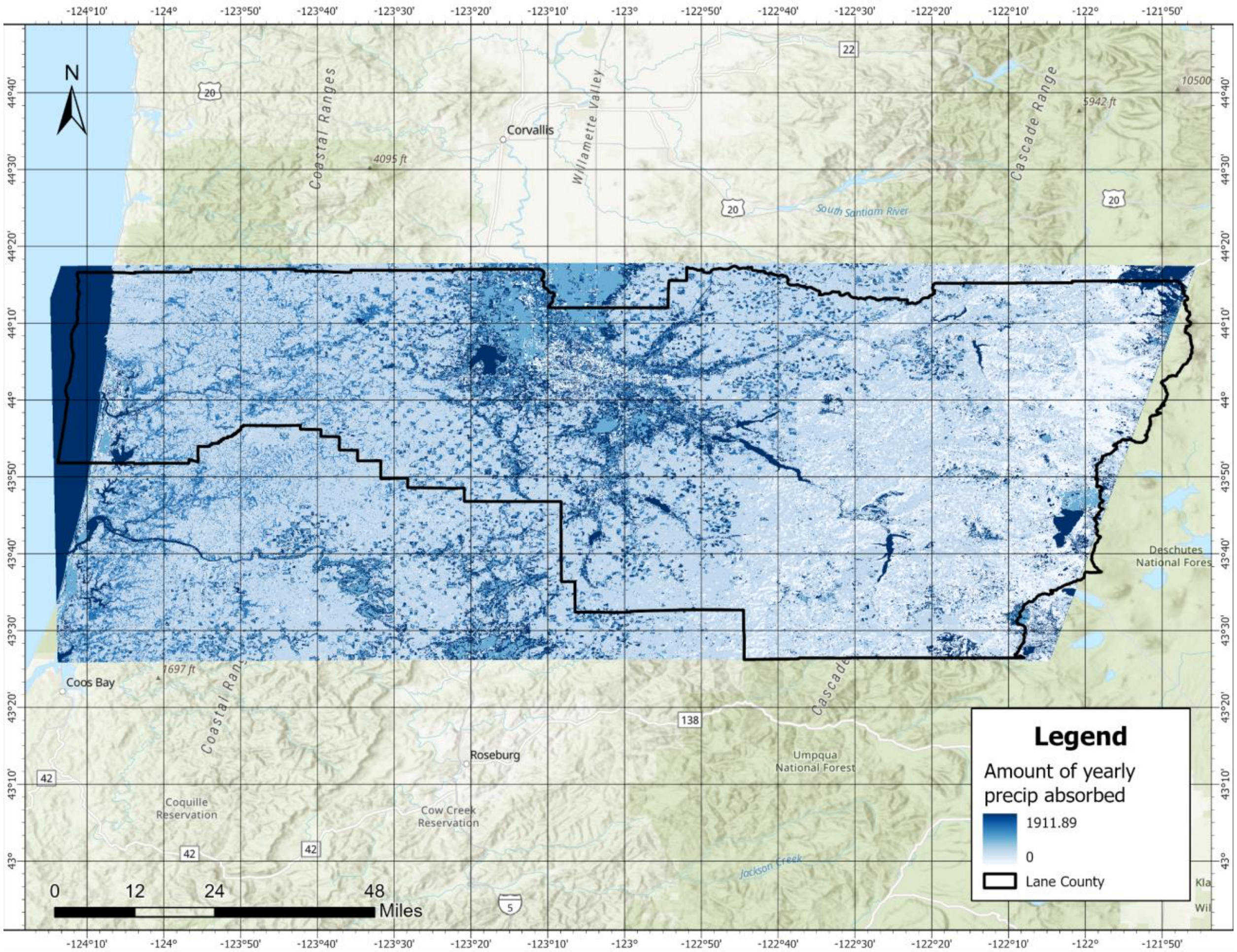


Figure 4: A map showing the amount of the yearly precipitation is predicted to make it into the aquifer system. Areas with water bodies such as oceans, rivers, and lakes will absorb the full yearly amount of precipitation, which is 1911.89 meters. This map was derived from Figure 3 by using the raster calculator to multiply by the yearly precipitation.

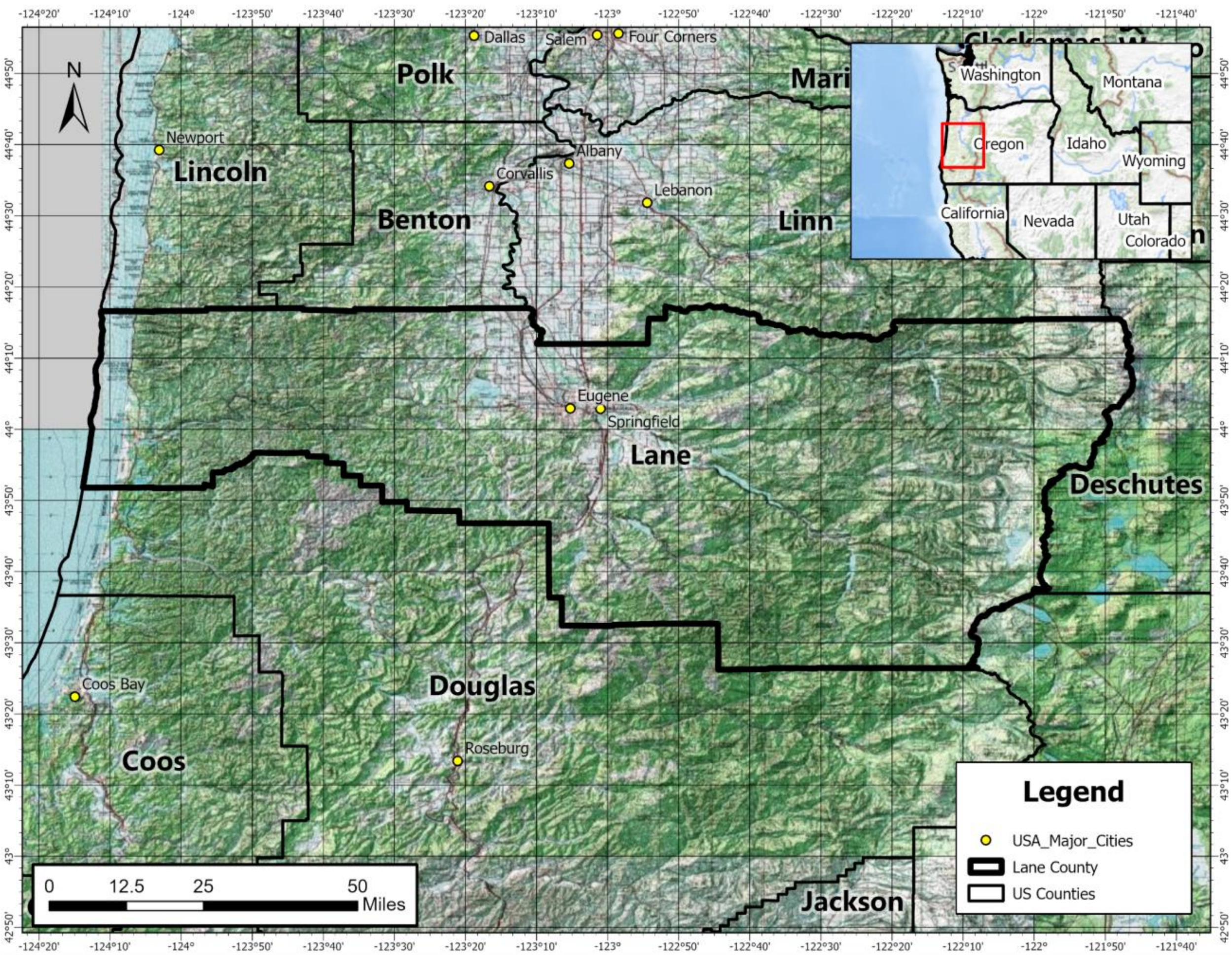
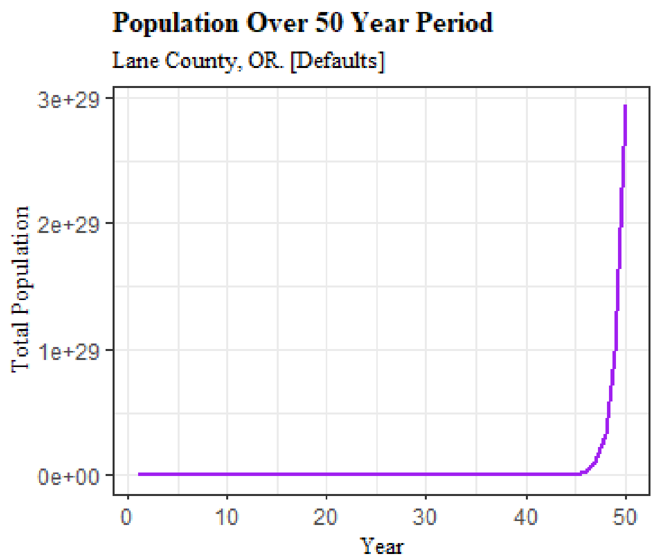
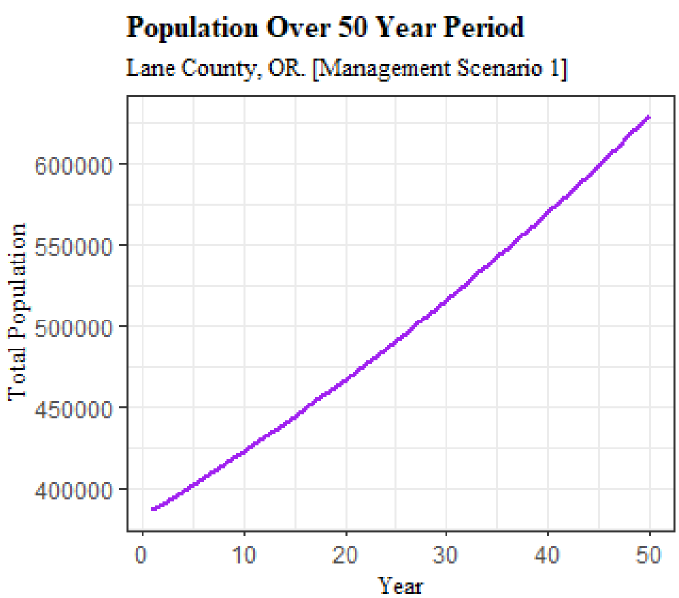


Figure 5: A map representing the study area for this project. An inset map shows the location within the northwest portion of the United States. Lane County has the thickest border, as it is our main study area. Major cities and county names have been added for reference purposes.





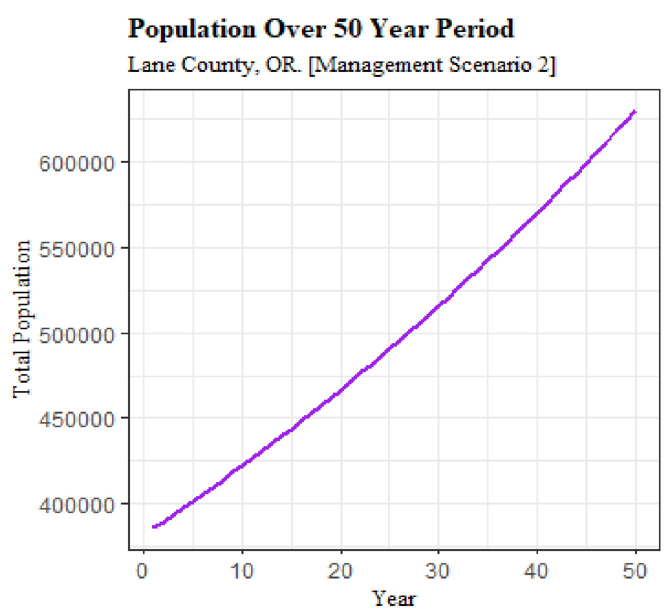


Figure 6: Population growth over a 50-year period for the Default Scenario with initial conditions as k=1.1, Management Scenario 1 where k was changed to 0.01 to match historical population growth of Lane County, and Management Scenario 2 where k was also 0.01.

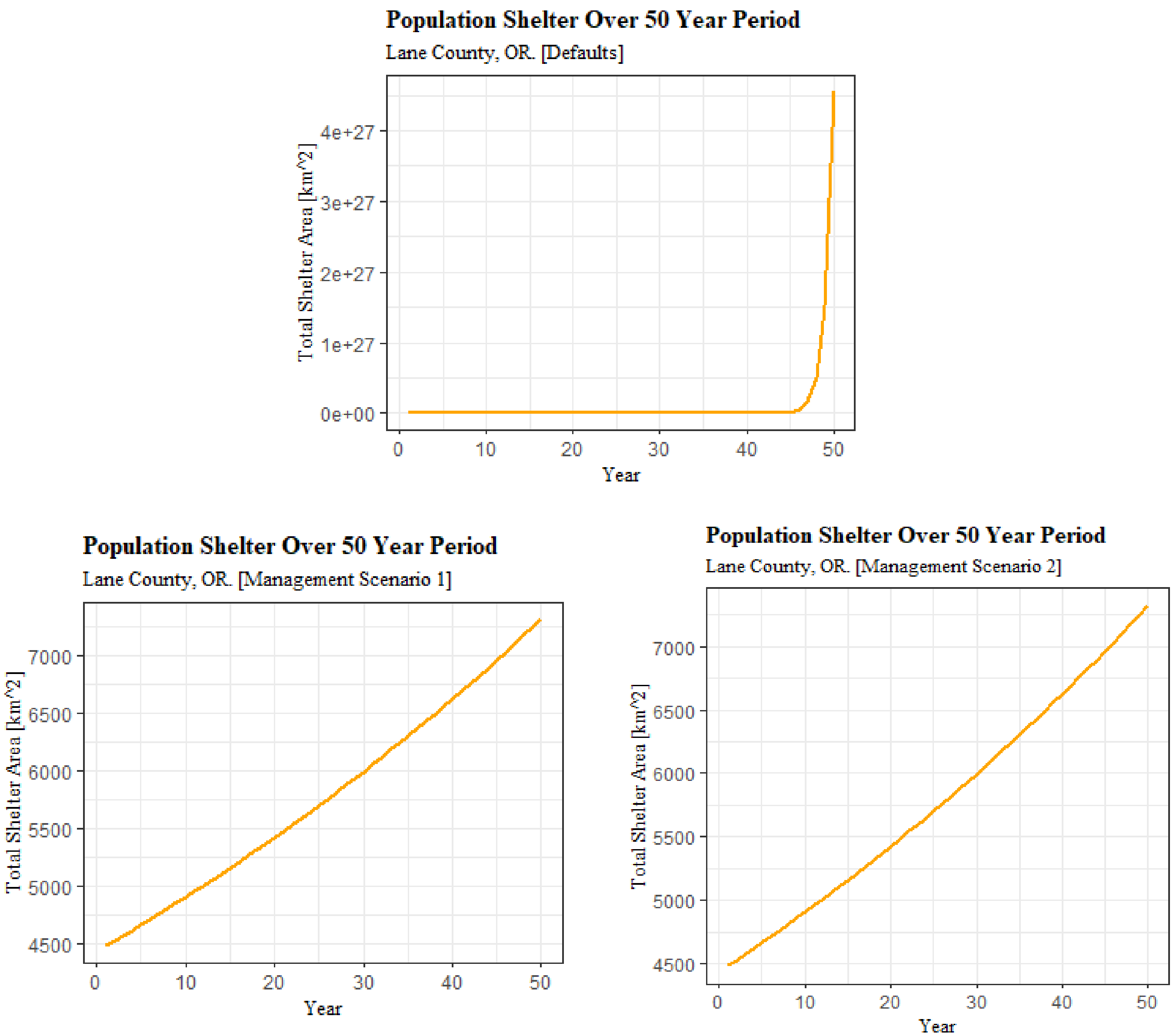


Figure 7: Total area [km^2] needed to meet population shelter requirements for the growing population of Lane County. For both management scenarios 1 and 2, the default number of people per household was changed from 6 to 8 and the residential requirement (93 m^2) was lowered from a growth rate of 10[m^2-yr] to a growth of 1 [m^2-yr] per residence.

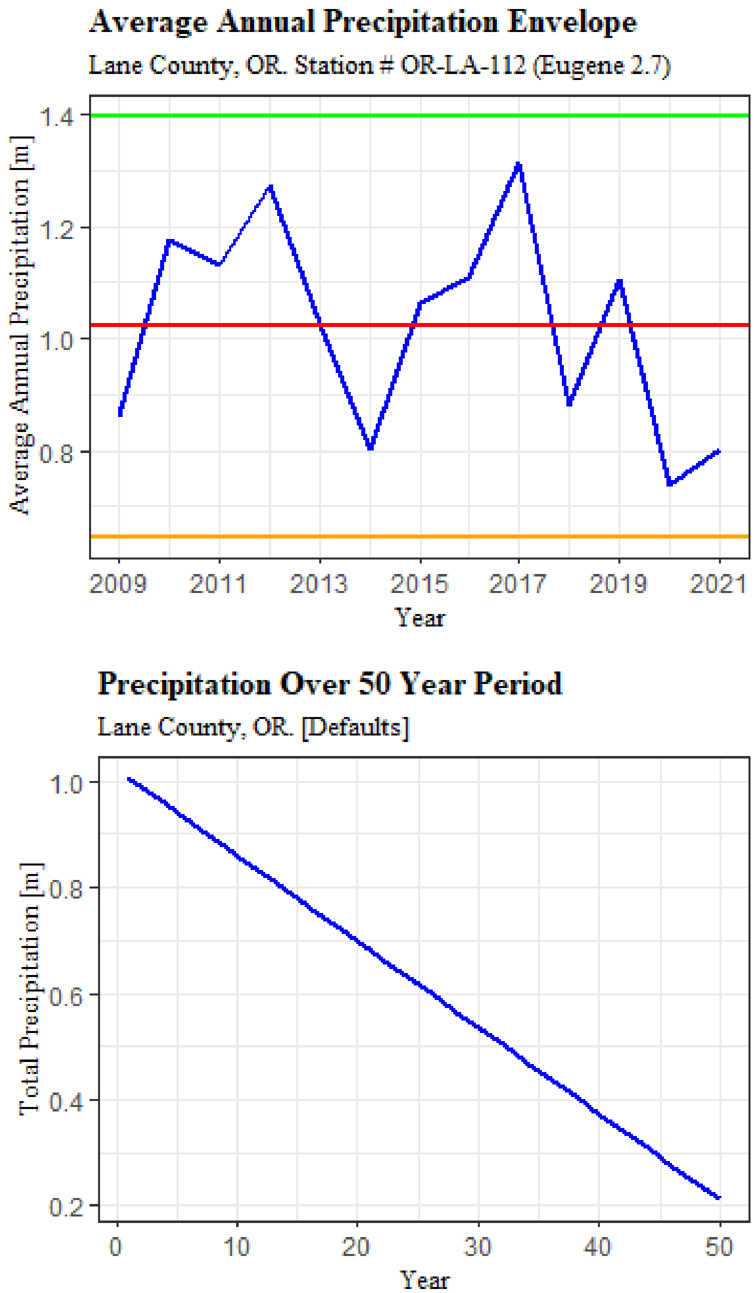


Figure 8: Precipitation Envelope [m] from 2009 to 2021 with the upper bound and lower bounds of precipitation 2 standard deviations away from the mean, and the downward linear precipitation trend over the 50 year period [m].

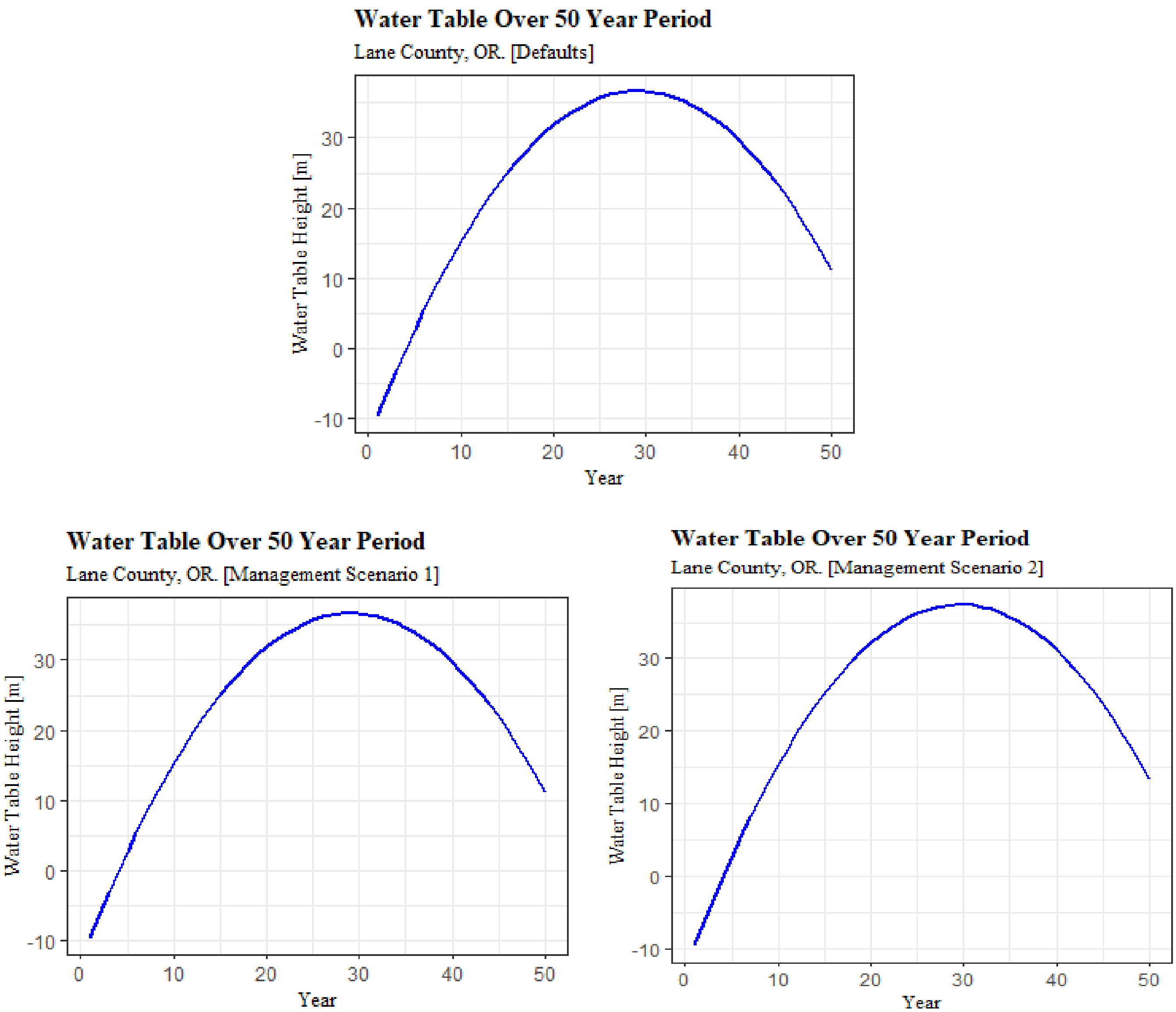


Figure 9: Water Table [m] over a 50 year period for each simulation. No water variables were changed for the Default Scenario and Management Scenario 1, but total water well output was decreased from 100% to 80% for Management Scenario 2 resulting in 0.77 m addition to the peak water table height (36.66 m to 37.43 m).

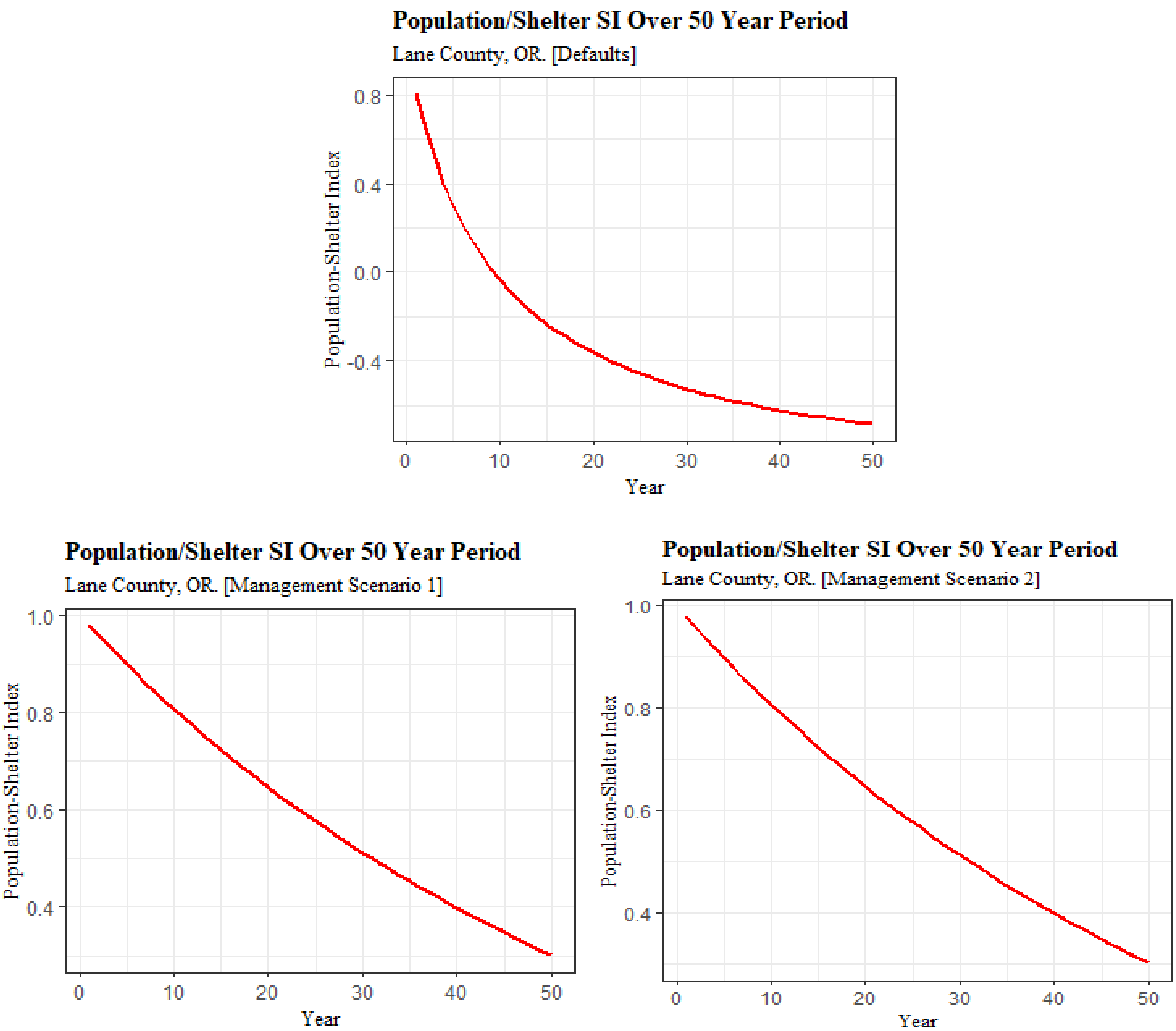


Figure 10: Population-Shelter Index over a 50 year period. For both Management Scenarios 1 and 2, the Defaults of k=1.1, N_p^0= 6, and $A_r^{\blacksquare}(t+1)$= 10 m^2-yr were changed to k=0.01, N_p^0 = 8, and $A_r^{\blacksquare}(t+1)$ = 1 m^2-yr to yield higher sustainability.

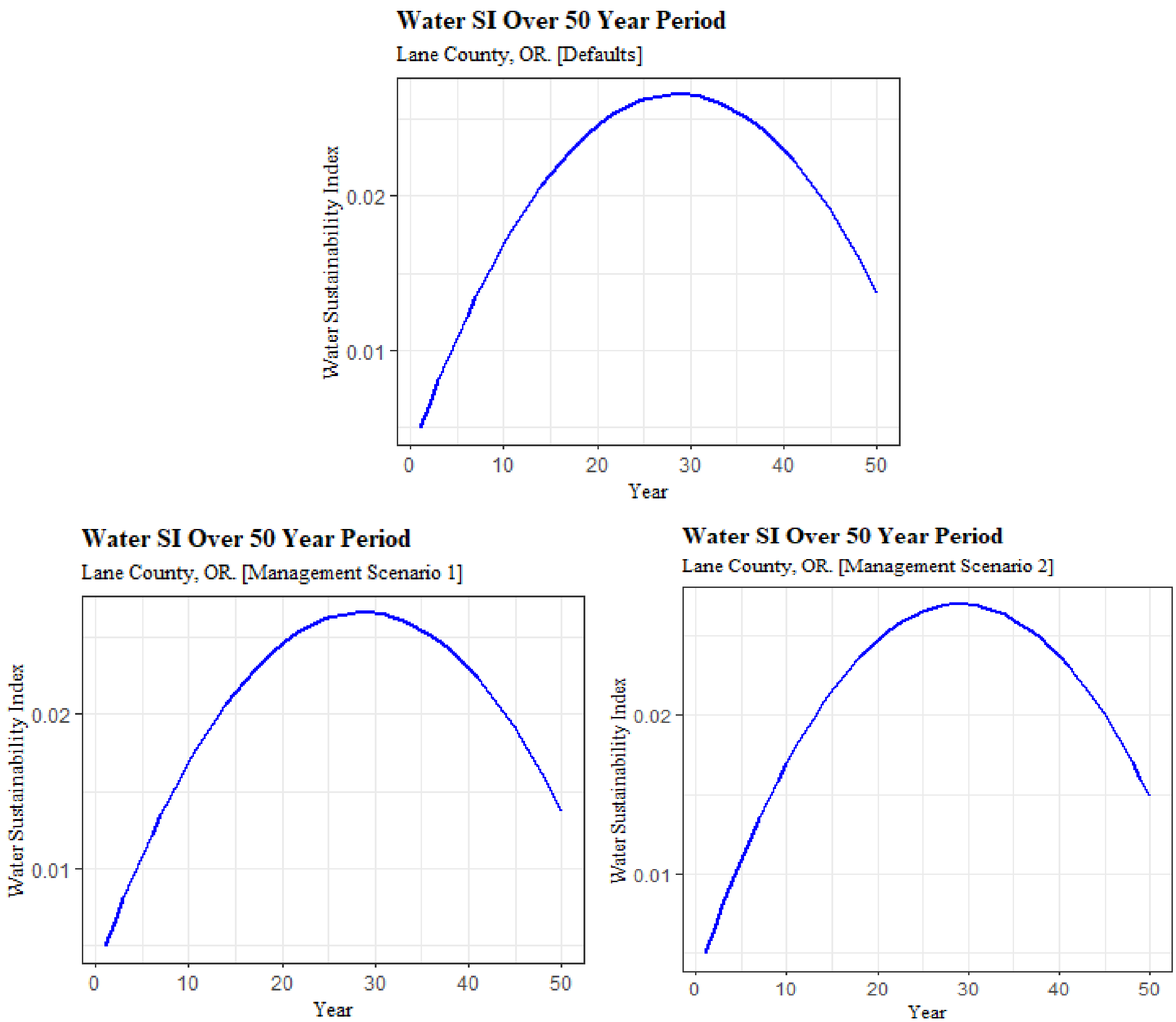


Figure 11: Water Sustainability index over a 50 year period. For both the Default scenario and Management Scenario 1, no water variables were altered. For Management Scenario 2, water well output was changed from 100% to 80% to reduce overall water consumption and increase water sustainability.

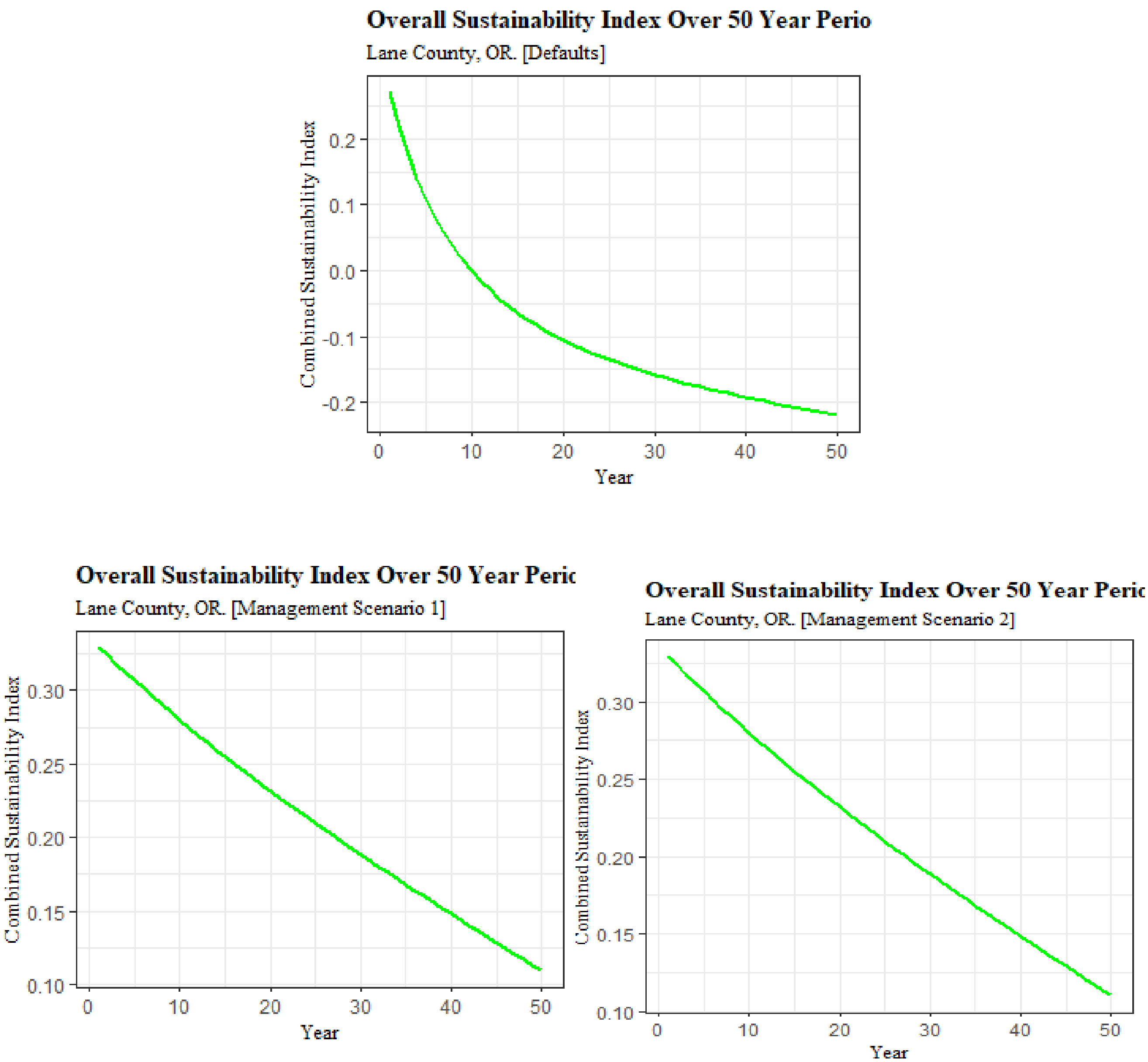


Figure 12: The combined overall Sustainability index for Lane County Oregon for the Default Scenario, Management Scenario 1, and Management Scenario 2. At the end of the 50 Year period: Default Scenario had a weighted sustainability index of -0.2196, Management Scenario 1 had a weighted sustainability index of 0.1093, and Management Scenario 2 had a weighted sustainability of 0.1101.

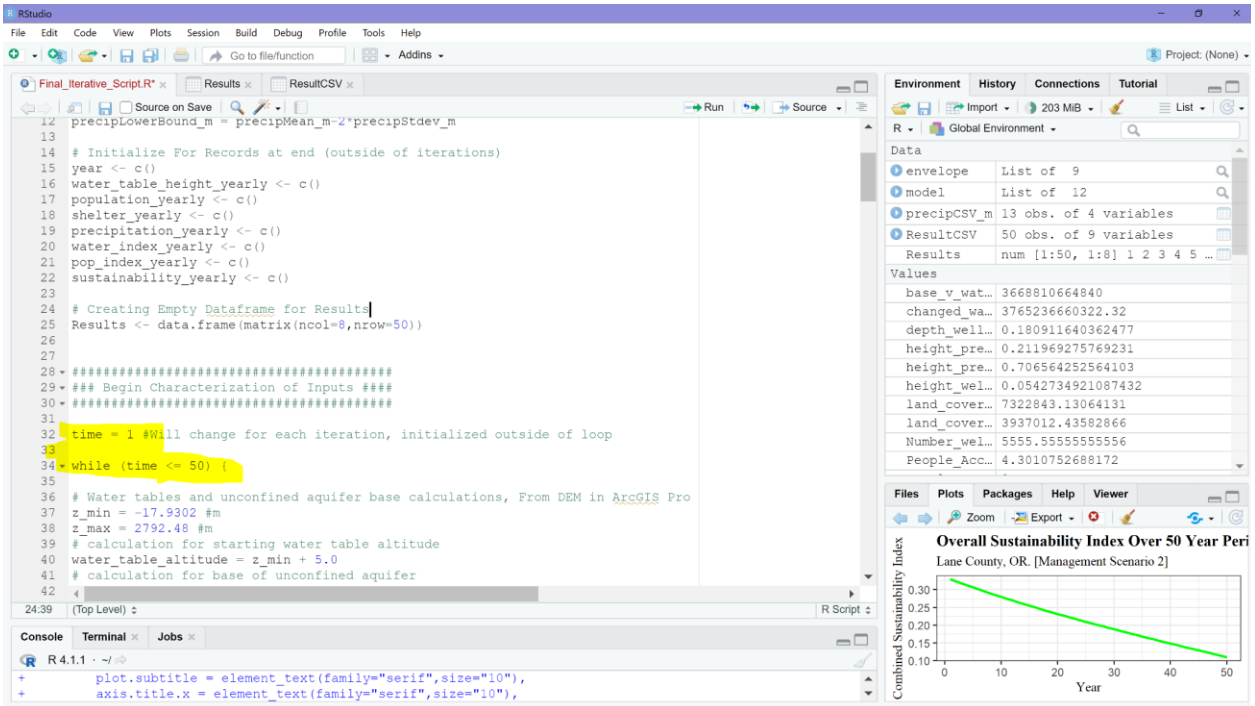


Figure 13: Depicts the R Script that runs each simulation. Highlighted is the [while loop] that iterates over the 50 years, with time updated at the end of each loop. This script streamlined tweaks to variables, since each number could be changed easily and the whole simulation ran again in seconds— with new figures that represented the new changes created simultaneously.