

**GIS Assessment of Groundwater Recharge Potential in
Whatcom County, Washington State: Implications for Land Use**

By

OLATUNBOSUN AYETAN

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Supervisors:

Dr. Heather Mackay

Professor Les Lavkulich

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EXECUTIVE SUMMARY

Ecosystem services such as groundwater recharge play an important role in sustainable management of groundwater resources. The present study was carried out to identify and map zones in the North Lynden Watershed Improvement District (NLWID) that have productive groundwater recharge potential using Geographical Information System (GIS). The NLWID is part of the Fishtrap Creek Watershed, which is faced with issues including land use changes and loss of resource land and farmlands that have the potential to reduce natural recharge of the Sumas-Abbotsford aquifer, which is an important source of water for domestic and urban supply, agriculture, fisheries and aquatic ecosystems. Storm water attenuation especially in winter is also an important issue to be solved in the study area. In the present study, the thematic layers considered were land curvature, geology, soil type, slope, land use/land cover, drainage density and precipitation. Individual layers were divided into various classes and ranked appropriately, then assigned weights based on their relative contribution to groundwater recharge. A penetrometer field test was also carried out to investigate soil compaction and the relationship between land cover and groundwater recharge potential. The thematic layers were integrated in ArcGIS for delineation of groundwater recharge potential zones. The recharge map thus obtained was divided into four zones (low, moderately low, moderate, high and very high recharge potential) based on their influence on groundwater recharge. The results indicated that about 43% and 0.009% of the study area has very high and low groundwater recharge potential respectively. The penetrometer field test qualitatively revealed that land cover and the required management practices in addition to the soil types can affect groundwater recharge potential. The results of the study can be used to formulate an efficient groundwater recharge management plan for sustainable utilization of limited groundwater resources

1.0 INTRODUCTION

Ecosystem goods and services are the benefits provided to humans by the ecological functioning of healthy productive ecological systems (Millennium Ecosystem Assessment, 2005). The services include provisioning services such as food, water, timber, fiber, and genetic resources; regulating services such as the regulation of climate, floods, pollination, groundwater recharge, disease, and waste treatment; the cultural services include recreation, aesthetic enjoyment, and spiritual fulfillment; and supporting services such as soil formation, and nutrient cycling (Roy *et al.*, 2011). Humans depend on ecosystems to provide us with these necessities of life, but we have not been managing them well. For instance, humans have altered regulating services substantially by modifying the ecosystems providing the service (especially groundwater recharge) (Egoh *et al.*, 2007).

Green infrastructure can be defined according to Naumann *et al.*, (2011) (page 1), as “the network of natural and semi-natural areas, features and green spaces in rural and urban, terrestrial, freshwater, coastal and marine areas, which enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services”. Green infrastructure incorporates the natural environment and engineered systems to provide a wide range of benefits to people and wildlife by providing clean water and conserving the ecosystem functions (Benedict and McMahon 2002). It can also help to restore some of the natural processes required to manage water and create healthier urban environments by using soils, vegetation and other elements and practices. For instance, water supply from boreholes and agriculture depends on the groundwater resources being recharged, either naturally or artificially. Without the recharge, the water supply would need to be provided in some other (probably engineered) way. Spatial planning of infrastructure such as water supply should then take the “green infrastructure” as well as the built infrastructure into account, for planning and for budgeting purposes. Therefore, we need to be able to quantify and map ecosystem services across the landscape – so that this may be incorporated into the conventional spatial planning that is done by local governments such as that of Whatcom County, Washington State, United States of America.

Groundwater recharge is defined as water that infiltrates into the ground to a depth below the foundation zone (Chachadi, 2015). An important aspect of managing groundwater involves understanding how, where and how much groundwater resource is being replenished or recharged (Chachadi, 2015). As water moves from the surface through the unsaturated zone a proportion is lost to evaporation, some is taken up by plants (evapotranspiration) and some stays within the unsaturated zone. These processes determine a precipitation threshold above which groundwater recharge will effectively occur. Rainfall amounts below the recharge threshold create very little or no contribution to groundwater

recharge. The significance of each factor controlling recharge can vary from place to place and can vary over time as land-use and vegetation cover changes (Chachadi,2015). The removal of deep-rooted plants such as trees (which help create macropores in the soil) in favour of row crops, or plantation establishment in former pasture country can have a negative impact on the volume of water entering groundwater systems (Benyon *et al.*, 2006). It may be necessary to manage land use to safeguard the volume of water getting into aquifer systems (MacDonald and Calow, 2009). The sources of recharge to a groundwater system include both natural and anthropogenic phenomena. Examples of natural sources include recharge from precipitation, lakes, ponds, and rivers, and from other aquifers. Anthropogenic sources of recharge include irrigation losses from canals and fields, septic tanks, sewers, leaking water mains and over-irrigation of parks, gardens, and other public amenities. Recharge from these sources has been classified as direct or diffuse recharge from percolation of precipitation and indirect recharge from runoff ponding (Chachadi,2015).

This project will study and map (using Geographic Information Systems) regions capable of groundwater recharge about the effects of land use change on groundwater recharge and water resource dynamics as it influences agricultural enterprises (Mackay, 2019 *personal communication*). Also, climate change is likely to lead to increased demand for water, especially in summer and there are not many good options for surface water storage in dams, plus, population growth will increase water demand, groundwater recharge to aquifers such as the Sumas-Abbotsford aquifer can be affected by land cover and land use.

1.1 OBJECTIVES

- To determine, assess and map groundwater recharge potential in the North Lynden WID.
- To determine how recharge potential may be affected by land-use and land cover.
- To identify and delineate areas that have potential for groundwater recharge in the landscape
- To develop groundwater recharge map that can be incorporated into the conventional spatial planning carried out by local governments in the Whatcom County, Washington State, United States of America.

2.0 STUDY AREA (NORTH LYNDEN WATERSHED IMPROVEMENT DISTRICT, NOOKSACK WATERSHED, WHATCOM COUNTY, WASHINGTON STATE)

The Nooksack Watershed (Figure 1) covers over 830 square miles (2150 square kilometers) in Whatcom County (Northwestern Washington) and British Columbia. The middle fork of the Nooksack River begins at Mount Shuksan, in North Cascades National Park, and the north and south forks flow from Mount Baker, at 10,778 feet, and Twin Sisters Mountain. Glacier melt, snowmelt, groundwater, and rainfall feed the 1,400 stream and river miles that comprise the watershed. Most of the upper watershed is Federally owned, but the middle section consists of private land, state land, and small landowner forestry operations. The lower portion of the watershed is still rural, but more heavily developed than the upper reaches, with farms and residences dominating the landscape (Puget Sound Institute, 2019). The Sumas-Abbotsford aquifer underlies the agricultural lowlands, and the main recharge areas are in the lowlands and foothills (Lin *et al.*, 2018).

The North Lynden Watershed Improvement District (WID) (Figure 1) concern is to alleviate the damage that flood waters can cause on farms in the area, it is located within the Nooksack watershed and was established in March 2007 by landowners who were affected by severe flooding. With the help of community volunteers, Whatcom County Agricultural Preservation Committee and Whatcom Conservation District, a petition process was initiated to create a nearly 6,000-acre district which turned out to be the North Lynden Improvement District (NLWID, 2018). Like other areas in the lowlands of western Whatcom County, Washington State, North Lynden gets 1,067 mm (42) inches of rain, on average, per year, and average of 178mm (7 inches) of snow per year. Geographically, it is an extension of the Lower Mainland area of British Columbia, essentially the lowland delta plain of the Fraser River.

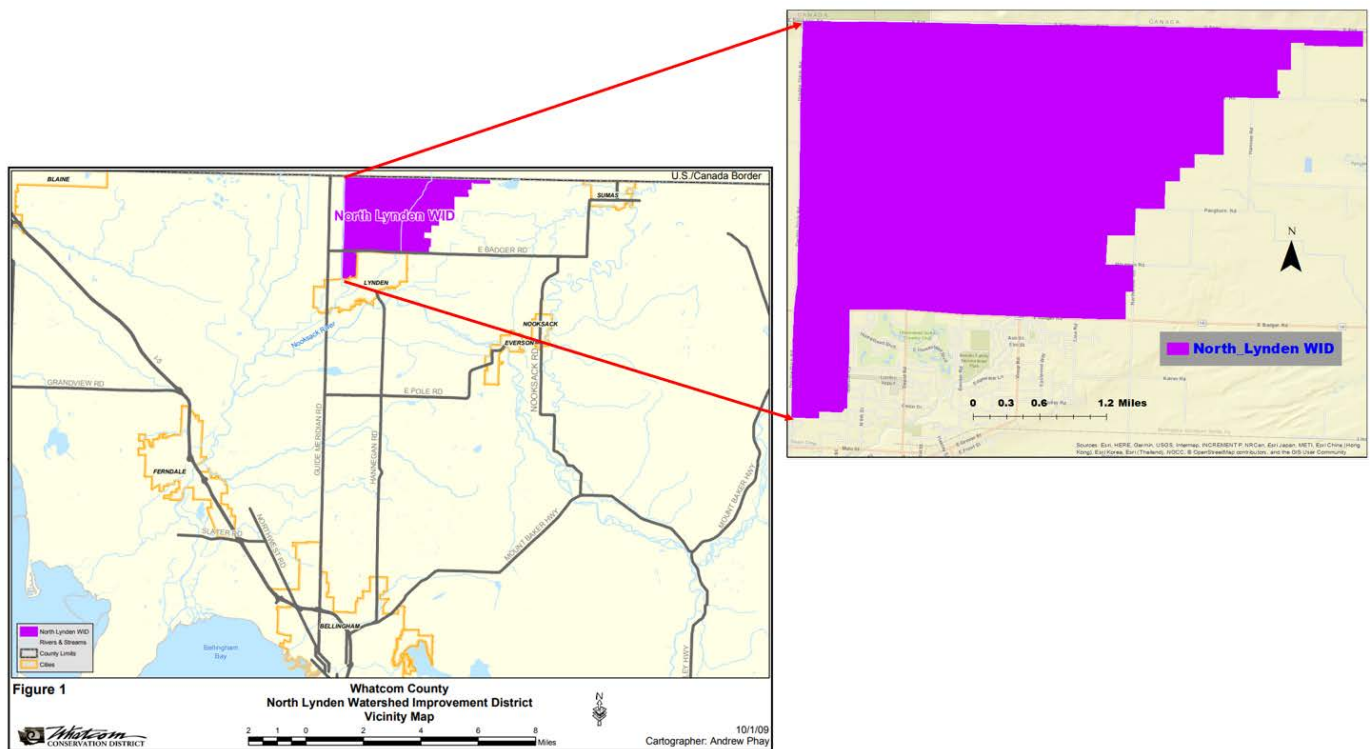


Figure 1. Location of North Lynden WID in Whatcom County

Groundwater levels in the aquifers of the study area fluctuate because of changes in the rates of recharge to and discharge from the aquifers. When recharge exceeds discharge, groundwater levels rise and groundwater storage increases; conversely, when discharge exceeds recharge, groundwater levels decline and groundwater storage decreases (Gendaszek, 2014). Precipitation infiltrates the land surface and percolates through the unsaturated zone to the water table and recharges the aquifers. Precipitation is not evenly distributed throughout the year; most rainfall occurs between November and March, whereas snowmelt is greatest during April and May resulting in seasonal variability in recharge to aquifers in the study area. Surface-water features such as streams also provide recharge to underlying aquifers when surface-water stages exceed groundwater levels (Gendaszek, 2014). Streamflow and stage of the SF Nooksack River is greatest because of storms during the autumn and early winter (November through January) and following the melting of the snowpack during the spring freshet in May. Streamflow and stage reach an annual minimum during August and September during the dry season and following the melting of the snowpack (Gendaszek, 2014).

Fishtrap Creek enjoys relatively stable, high quality water flows, which is derived from a combination of rainfall driven surface water and significant groundwater sources. The annual precipitation ranges between 50-60 inches of rainfall, which supports Fishtrap Creek average monthly flows ranging between a few cubic feet per second (cfs) in August to 160 cfs (4.53 m³/s) in January. An estimated 82% of the flow in Fishtrap creeks is generated in the urbanizing Canadian portion of the

watershed. A two-year storm can be expected to produce a flow of 586 cfs (16.59 m³/s) at Front Street in Lynden while a 25-year storm may produce flows of 1100 cfs (31.15 m³/s) (Whatcom Conservation District, 2009).

According to Whatcom Conservation District, 2009 report, there are extensive, sub-surface, tile drainage systems installed in the NLWID. Approximately 30 miles of farm field ditch drain crop and pasture land. Water table on many fields is also controlled through sub-surface (tile) drainage installed at 2 to 4 feet depth. An estimated 350-400 thousand feet of sub-surface drains are installed to improve drainage of crop and pasture land on the WID.

3.0 METHODS

3.1 PART A: Groundwater Recharge Potential Zones Mapping by GIS Analysis

3.1.1 Preparation of Thematic Layers

In the present study, GIS techniques were used for the delineation of potential groundwater recharge zones by considering a multiparametric data set comprising of seven thematic layers: curvature, geology, land use/land cover, slope, drainage density, precipitation and soil type. The file geodatabase for the Whatcom County soil map and the Digital Terrain Model were obtained from the Whatcom Conservation District, whereas the land use/land cover, geology and precipitation (Average Annual Precipitation 1981-2010) datasets were obtained from the USDA geospatial data gateway (<https://datagateway.nrcs.usda.gov/>). The crop distribution data (for 2018) was downloaded from the Washington State Department of Agriculture website. Thematic layers of curvature, slope and drainage density were extracted from Digital Elevation Model (DEM) obtained from the USGS earth-explorer website (<https://earthexplorer.usgs.gov/>). After preparing all the thematic layers, different features/classes of the individual themes were identified and then assigned suitable weights according to their relative importance in groundwater recharge from literature review (Table 1) (Singh *et al.*, 2013; Yeh *et al.*, 2016; Gnanachandrasamy *et al.*, 2018). All the weighed thematic layers were integrated and processed using ArcGIS 10.6.1 (ESRI 2018) to demarcate potential groundwater recharge zones.

Table 1. Factors taken in assigning weightage with relations to groundwater recharge potential

Thematic map	Weightage Class	Recharge Potential
Curvature	Very Concave	High
	Concave	Moderately High
	Flat	Moderate
	Convex	Moderately Low
	Very Convex	Low
Geology	Alluvium and Outwash.	High
	Argillite, Glacial drift, Landslide, Moraine and Till	Moderate
	Andesite, Arkose, Conglomerate, Dunite, Graywacke,	Low
	Greenstone, Metasedimentary rock, Phyllite, Quartz diorite, Serpentine, and Volcanic rock (aphanitic).	
	Water	Very Low
Land use/ land cover	Open Water	Very Low
	Unclassified, Developed-medium-intensive, Developed-high-intensive, and Barren land	Low
	Developed-open-space, and Developed-low-intensive	Moderate
	Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Herbaceous, Hay/Pasture, Cultivated Crops, Woody Wetlands and Emergent Herbaceous Wetland	High
Slope	Gentle Slope (0-1%)	High
	Moderately sloping (1-3%)	High
	Moderate steep sloping (3-5%)	Moderate
	Steep sloping (5-10%)	Low
	Very steeply sloping (>10%)	Low
Drainage Density	High	Unsuitable for recharge
	Moderate	Moderately suitable for recharge
	Low	Suitable for recharge
Precipitation	31-35 inches	Low
	36-50 inches	Moderate
	51-80 inches	Moderate
	81-100 inches	High
	101-188 inches	High
Soil (Infiltration)	Good	High
	Moderate	Moderate
	Poor	Low

3.1.2 Weights Assignment and Integration of Thematic Layers

Table 2 and Table 3 present the different factors taken and assigning weightage with respect to groundwater recharge potential. All variables were normalized by rescaling to 0-1 according to their minimum/maximum value for each thematic layer and their features (Gnanachandrasamy *et al.*, 2018). In other words, to compute the normalized weight, each assigned weight was divided by the sum of all weight (Table 2), while for normalized ranking, individual ranks were divided by the highest, for all variables to fall between 0 and 1. To establish the potential zone of groundwater, all the thematic layers were converted into raster format and overlaid. To compute the groundwater potential index, the total weights of different thematic layers were integrated using the equation below (Rao and Briz – Kishore 1991):

$$GWPI = ((CVw)(CVwi) + (GGw)(GGwi) + (LLw)(LLwi) + (SLw)(SLwi) + (DDw)(DDwi) + (PRw)(PRwi) + (STw)(STwi))$$

Where, GWPI- groundwater potential index, CV-curvature, GG-geology, LL-land use/land cover, SL- slope, DD-drainage density, PR- precipitation, ST-soil type, and the subscript “w” and “wi” refer to the normalized weights of layer and the normalized ranking in each thematic layer, respectively. According to GWPI, the final groundwater recharge potential map was classified into five zones and designated as High, Moderately high, Moderate, Moderately low and Low. Finally, a map showing the different groundwater recharge zones in the study area was prepared in ArcGIS 10.6.1 (ESRI 2018) software. The flowchart for the groundwater recharge potential mapping is illustrated in Figure 2.

Table 2. Weights of seven layers used for mapping groundwater recharge potential

Layer	Assigned weight	Normalized weight
Curvature	8	0.23
Geology	7	0.20
Land use/land cover	6	0.17
Slope (%)	5	0.14
Drainage (km/km ²)	4	0.11
Precipitation (inches)	3	0.09
Soil	2	0.06

Table 3. Thematic layers with classes and assigned ranking

Layer	Class	Assigned Ranking	Normalized Ranking
Curvature	Very Concave	5	1.00
	Concave	4	0.80
	Flat	3	0.60
	Convex	2	0.40
	Very Convex	1	0.20
Geology	Alluvium and Outwash.	3	1.00
	Argillite, Glacial drift, Landslide, Moraine and Till	2	0.67
	Andesite, Arkose, Conglomerate, Dunite, Graywacke, Greenstone, Metasedimentary rock, Phyllite, Quartz diorite, Serpentine, and Volcanic rock (aphanitic).	1	0.33
	Water	0	0
Land use/land cover	Open Water	0	0
	Unclassified, Developed-medium-intensive, Developed-high-intensive, and Barren land	1	0.33
	Developed open-space, and Developed low-intensive	2	0.67
	Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Herbaceous, Hay/Pasture, Cultivated Crops, Woody Wetlands and Emergent Herbaceous Wetland	3	1.00
Slope (%)	Gentle Slope (0-1%)	3	1.00
	Moderately sloping (1-3%)	3	1.00
	Moderate steep sloping (3-5%)	2	0.67
	Steep sloping (5-10%)	1	0.33
	Very steeply sloping (>10%)	1	0.33
Drainage Density (km/km ²)	< 1 (Extremely Low)	3	1.00
	1 to 2 (Low)	3	1.00
	2 to 4 (Moderate)	2	0.67
	4 - 6 (High)	1	0.33
	> 6 (Very High)	1	0.33
Precipitation (inches)	31-35 inches	1	0.33
	36-50 inches	2	0.67
	51-80 inches	2	0.67
	81-100 inches	3	1.00
	101-188 inches	3	1.00
Soil	Good	3	1.00
	Moderate	2	0.67
	Poor	1	0.33

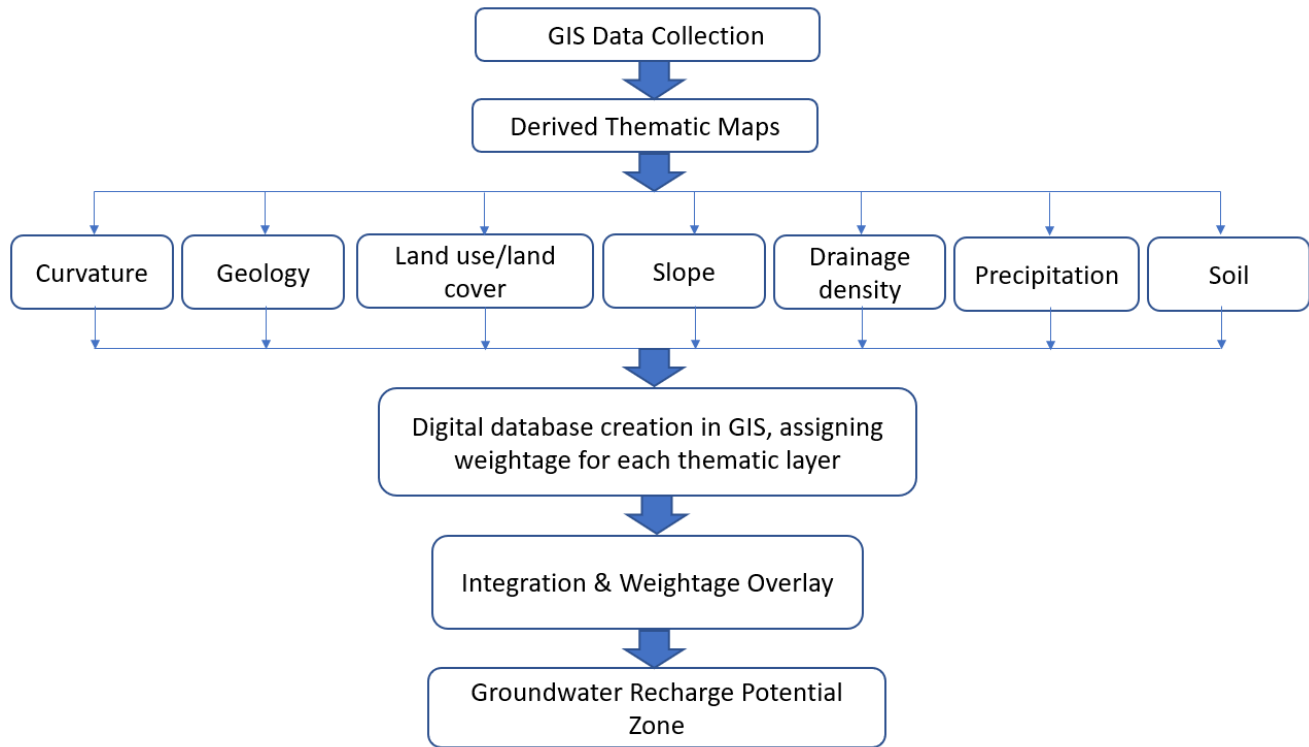


Figure 2. Flowchart for delineating potential groundwater recharge zones.

3.2 PART B: Soil Compaction Field Test using a Penetrometer

The penetrometer test was carried out to qualitatively investigate the effects of agricultural land use and crop types on recharge and discharge relationships in the North Lynden Watershed Improvement District. Penetrometer resistance was used as an indicator of any compacted regions within the soil profile. The measurements were taken to ground-truth the recharge potential at different sites, by qualitatively verifying if soil compaction varied within a map unit, thus affecting groundwater recharge potential.

Soil compaction occurs when soil particles are pressed together, reducing pore spaces between them (Jodi, 2018). Heavily compacted soils have greater density, few large pores, and less total pore volume. Compacted soil has a reduced rate of both water infiltration and drainage (Jodi, 2018). This happens because more water moves downward through the soil by large pores than smaller pores. Therefore, while soil compaction increases soil strength – the ability of soil to resist being moved by an applied force also means roots must exert greater force to penetrate the compacted layer. This means that a compacted soil has few macropores, hence, less groundwater recharge.

The penetrometer which is designed to mimic a plant root, consists of a 30° circular stainless-steel cone with a driving shaft and a pressure gauge. The readings (also called cone index) is taken by driving the rod into the soil at approximately one inch per second. The gradients on the rod shows the

depth of penetration and the depth at which the 300psi is exceeded shows point of severe compaction. For each measuring point, there are two numbers; the top of the compaction zone and the bottom of the compaction zone (Duiker, 2002).

In the present study, nine fields under different landcover were tested for soil compaction on five different locations in the North Lynden Watershed Improvement District. For each field, five to ten points were measured randomly for compaction, and in fields where patterns were recognized, the number of readings were increased. Readings were also taken for the top and bottom of the compaction zone of each random point. On fields with planted rows, measurements were taken in the row and interrow. Some of the tested fields are pasture, corn, hay fields, and mixed-forest park.

The penetrometer values were assigned to the mapped soil units. As the number of measurements were limited in this exploratory assessment, more measurements in each of the approximately 15 soil map units in the NLWID should be conducted to provide a more comprehensive evaluation for the study area.

4.0 RESULTS AND DISCUSSION

4.1 GIS Analysis Results

Curvature

The curvature function in ArcGIS displays the shape of a slope. The part of a surface can be concave or convex and the output of the curvature function can be used to describe the physical characteristics of a drainage basin in order to understand runoff and erosion process (ESRI 2016). The curvature value can be used to find soil erosion patterns as well as the distribution of water on land. In terms of groundwater recharge potential, convex shape has low potential, concave shape has high potential while flat surface has intermediate recharge potential. The curvature of the study area is divided into five classes from very convex to very concave (Figure 3a), where very concave has the highest recharge potential, followed by concave and flat. The North Lynden WID is relatively flat hence, falls within flat and concave curvature classes (Figure 3b).

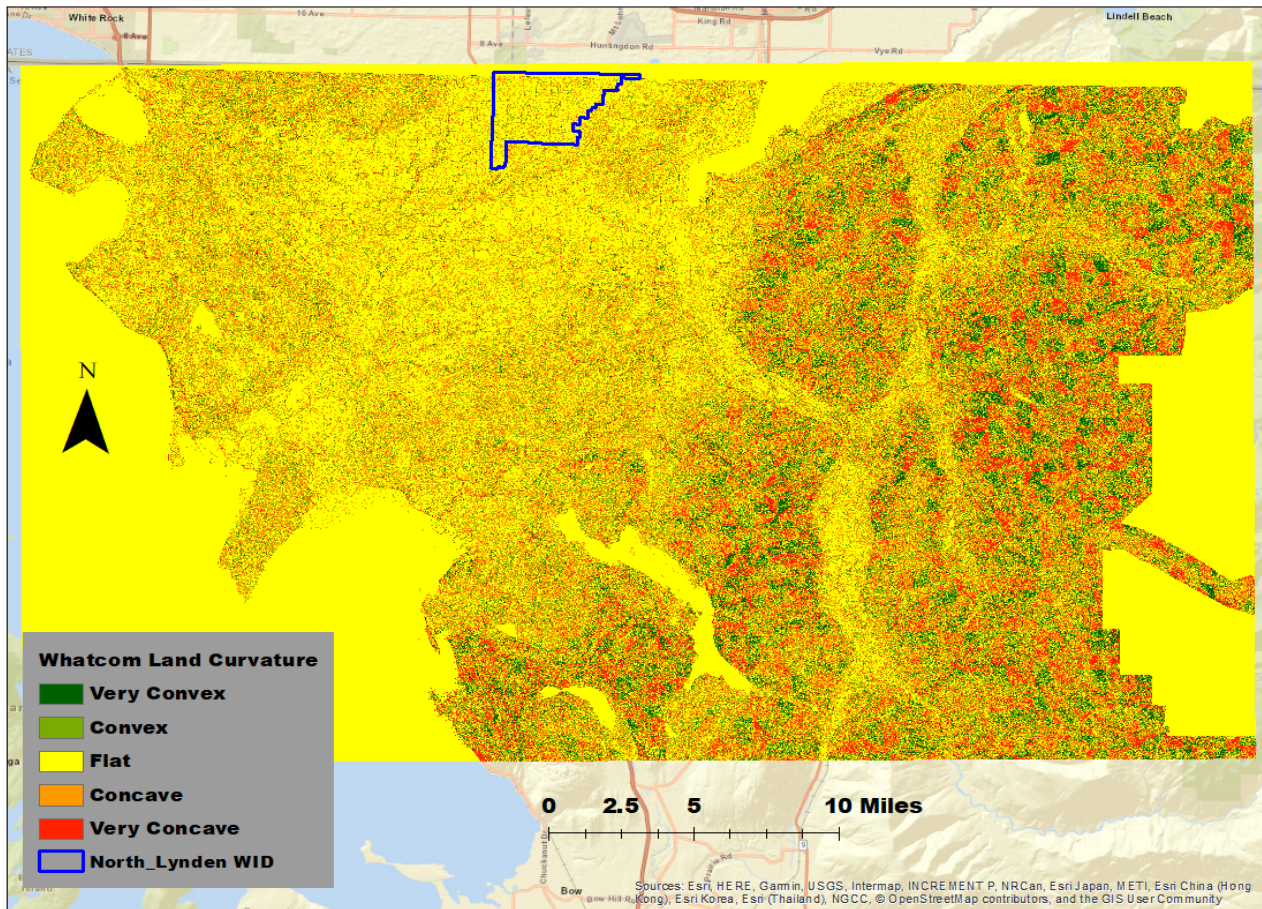


Figure 3a. Map of Whatcom County showing land curvature derived from Digital Terrain Model.

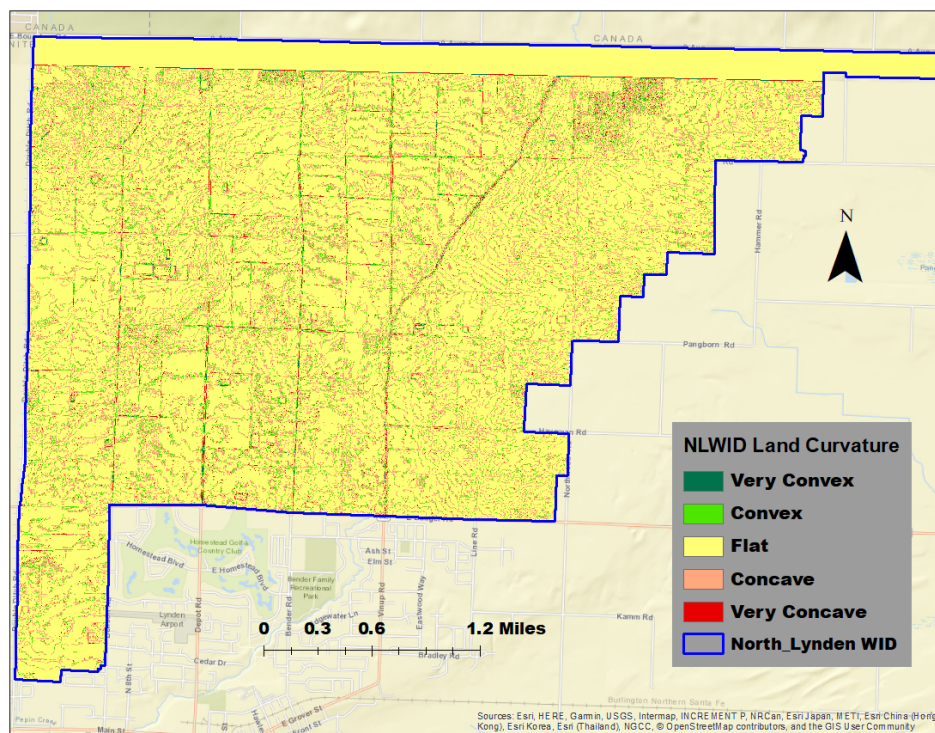


Figure 3b. Map of North Lynden WID showing land curvature derived from Digital Terrain Model.

Geology

There are about 18 different types of parent material found in the study area (Table 3). The alluvium and outwash rocks were ranked the highest potential for groundwater recharge based on rock characteristics such as infiltration rate, permeability and hydraulic conductivity (Blainey and Pelletier, 2008). The Geological map (Figure 4) of the present study was prepared with the help of Arc GIS software and the different geological structures were categorized under high, moderate and low recharge potential. The North Lynden WID is made up of one type of geologic material which is the Outwash plain, and this implies that the WID has a high potential for groundwater recharge based on the parent material characteristics. The outwash is formed of glacial sediments deposited by meltwater outwash at the end of a glacier (Gornitz, 2009).

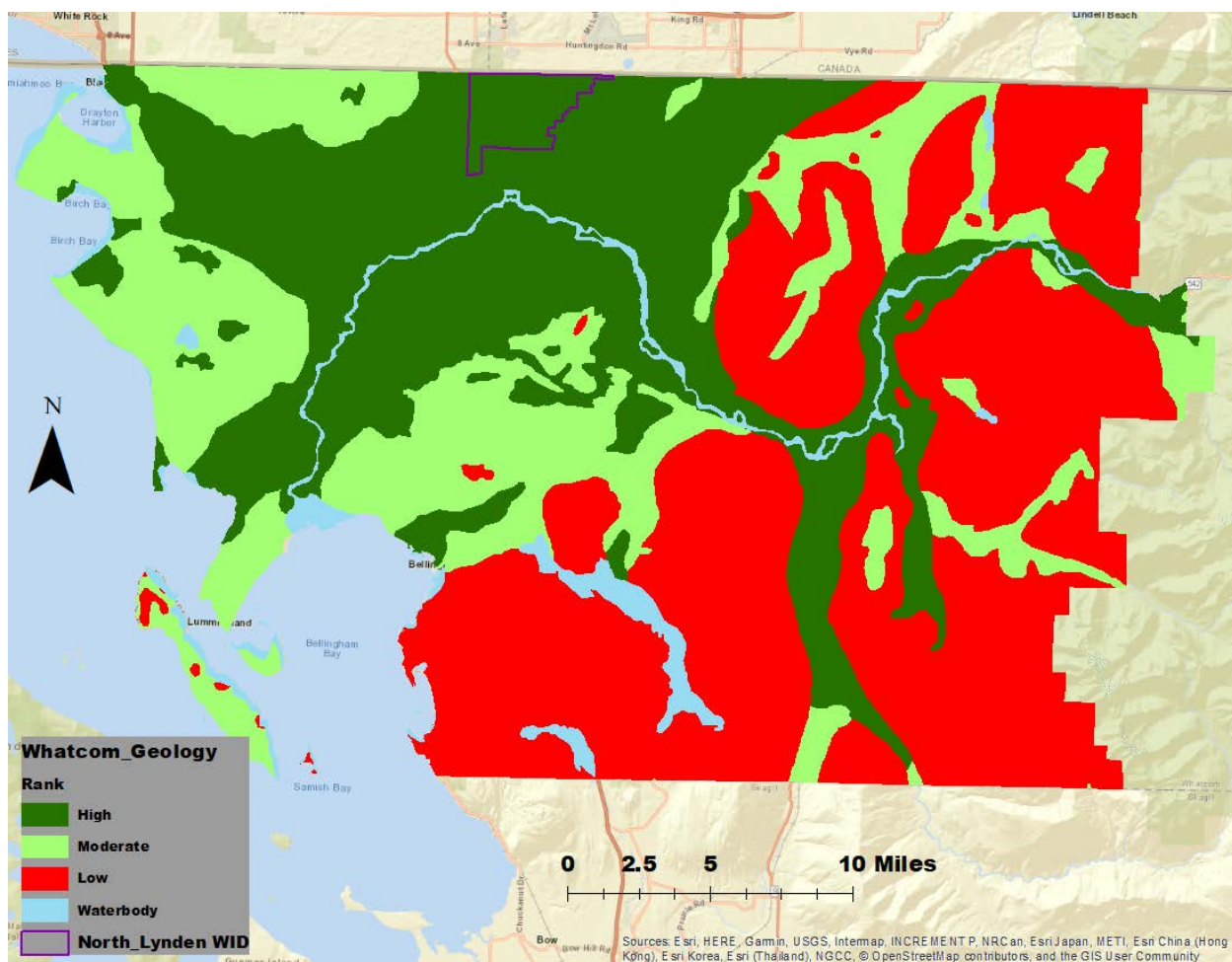


Figure 4. Map of Whatcom County showing the geology classification for recharge potential. Derived from datasets obtained from the USDA geospatial data gateway.

Land Use/ Land Cover (LULC)

Land use/land cover is an important determinant of groundwater recharge potential (Singh *et al.*, 2013). The rate and extent at which water infiltrate into the ground can be affected by the various

management practices associated with different LULC. For instance, the various root network of forest trees helps to reduce runoff and increase infiltration. Also, the tillage practices in agriculture can help to increase infiltration rate, while the use of heavy machinery can lead to soil compaction. There are about 15 different land uses/land cover in Whatcom County LULC in Whatcom County. The LULC were classified in terms of groundwater recharge potential as very low, low, moderate, high and very high (Figure 5), and the major LULC are forestry, cultivated crop and hay/pasture. In the North Lynden WID (Figure 6), the major LULC are cultivated crops and hay/pasture; considering the different cultural and management practices involved in the major LULC, some variations in groundwater recharge can be expected in the North Lynden WID.

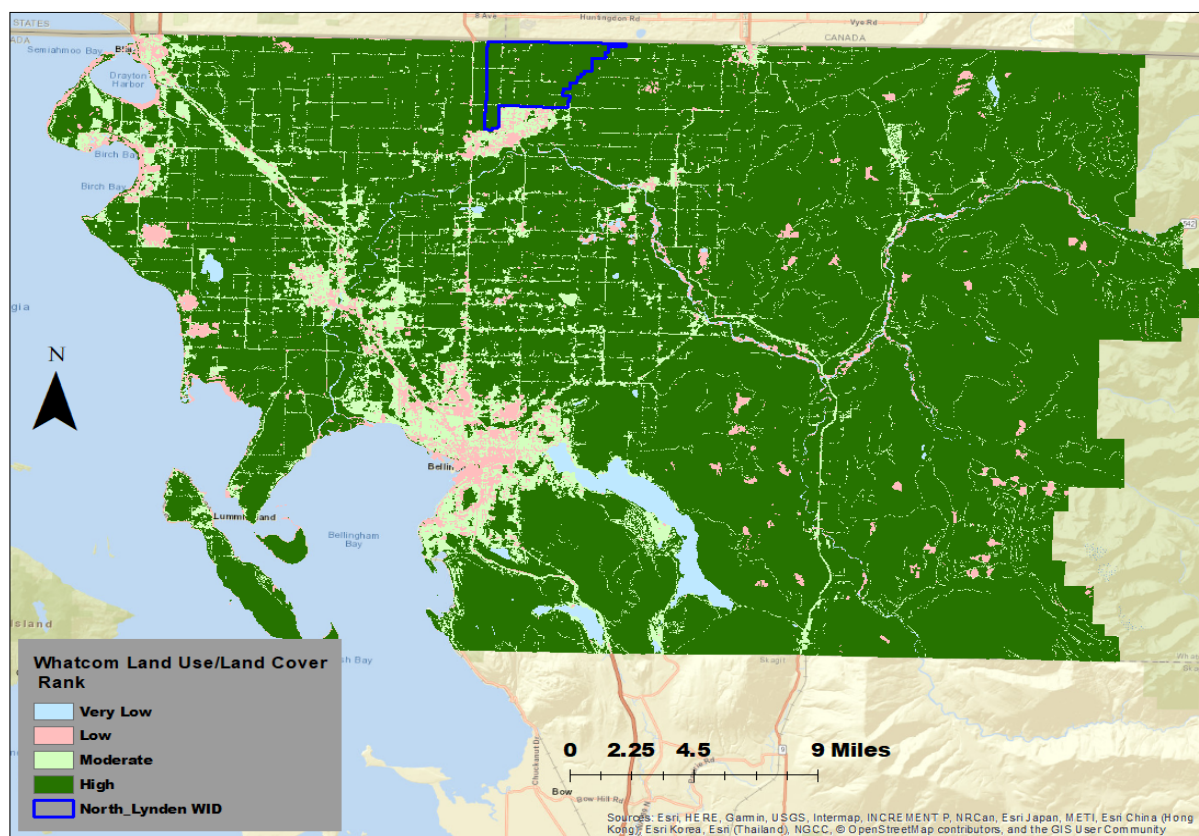


Figure 5. Map of Whatcom County showing the classification of Land use/Land Cover for recharge potential. Derived from datasets obtained from the USDA geospatial data gateway.

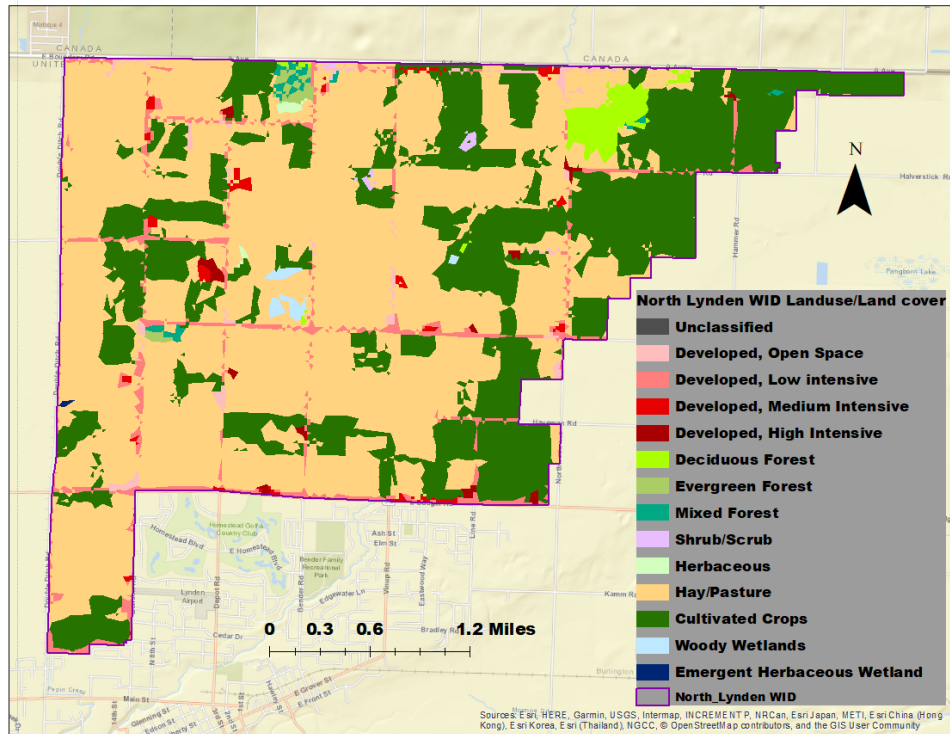


Figure 6. Map of North Lynden WID showing the classification of Land use/Land Cover for recharge potential.

Slope

In Whatcom County, slope varies from 0 to about 60 % (Goldin, 1992), with more gradient in the East than in the West (Figure 7). Flat plains can hold more rainfall and facilitate more recharge than elevated areas with higher slopes having high runoff and low infiltration rates (Singh *et al.*, 2013). Based on the slope, the County was divided into five slope classes; Gentle slope (0-1%), Moderately sloping (1-3%), Moderate steep sloping (3-5%), Steep sloping (5-10%), and Very steeply sloping (>10%) (Figure 8). The North Lynden WID falls within areas with 0-3% slope, which has high groundwater recharge potential. Areas in the Whatcom County with a slope ranging above 5% are considered to have very low groundwater recharge potential because higher slope facilitates high runoff, allowing less residence time for rainwater.

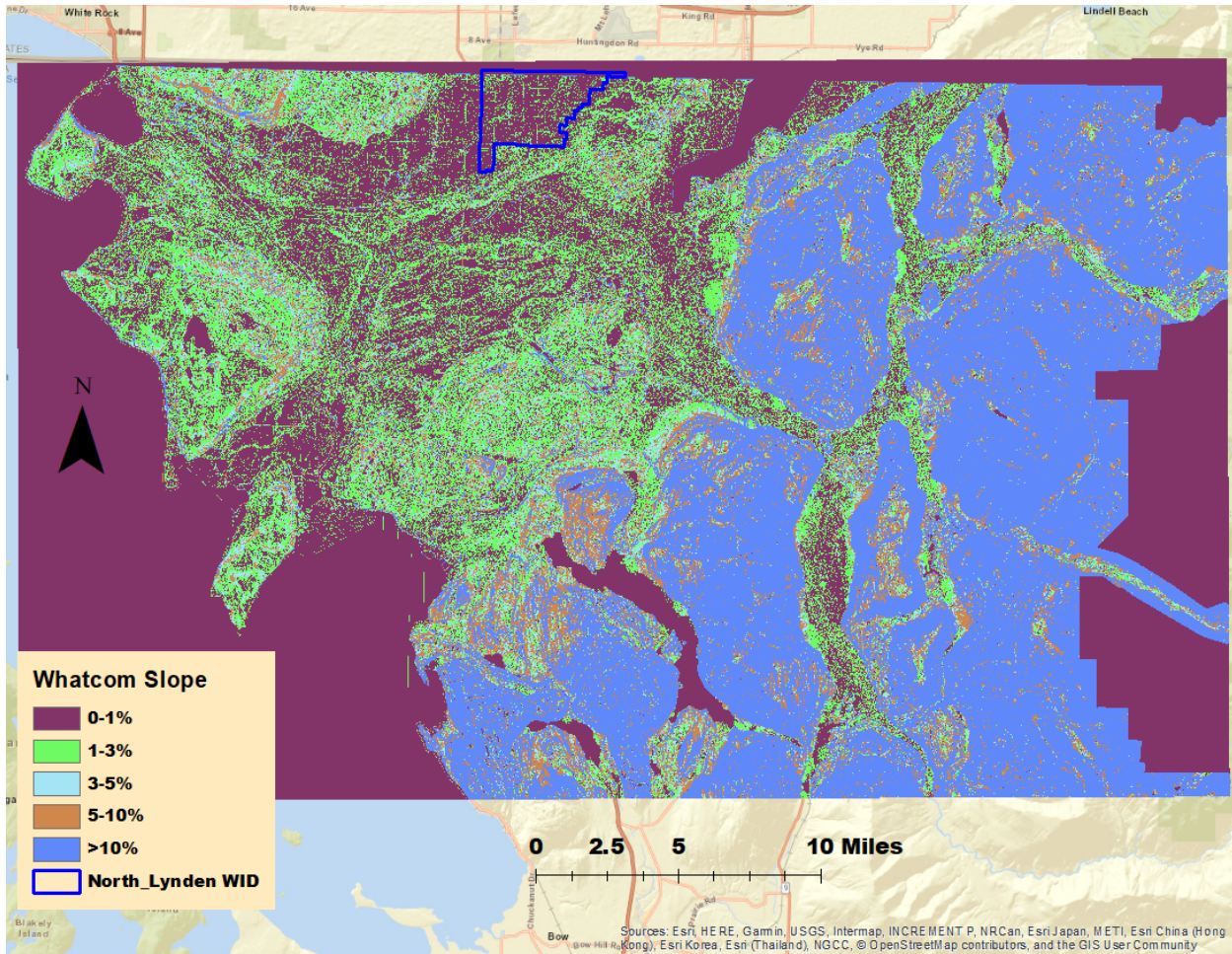


Figure 7. Map of Whatcom County showing slope classification, derived from Digital Terrain Model

Drainage Density

The drainage density is expressed as the sum of the length of stream orders per unit area (km/km^2) and indicates an expression of the closeness of spacing of channels (Singh *et al.*, 2013). It is an inverse function of permeability thus, indirectly indicates the suitability for groundwater recharge of an area and can also provide a significant indicator of percolation rate of water (Horton, 1945; Shaban *et al.*, 2006). In the study area, drainage density was classified into five classes and it varied from extremely low (<1) to very high (>6) (Figure 8). Higher ranking was given to an area with very low drainage density whereas lower ranking was given to an area with very high drainage density. The North Lynden WID has from low to moderate drainage density, which means that it has high groundwater recharge potential based on drainage density.

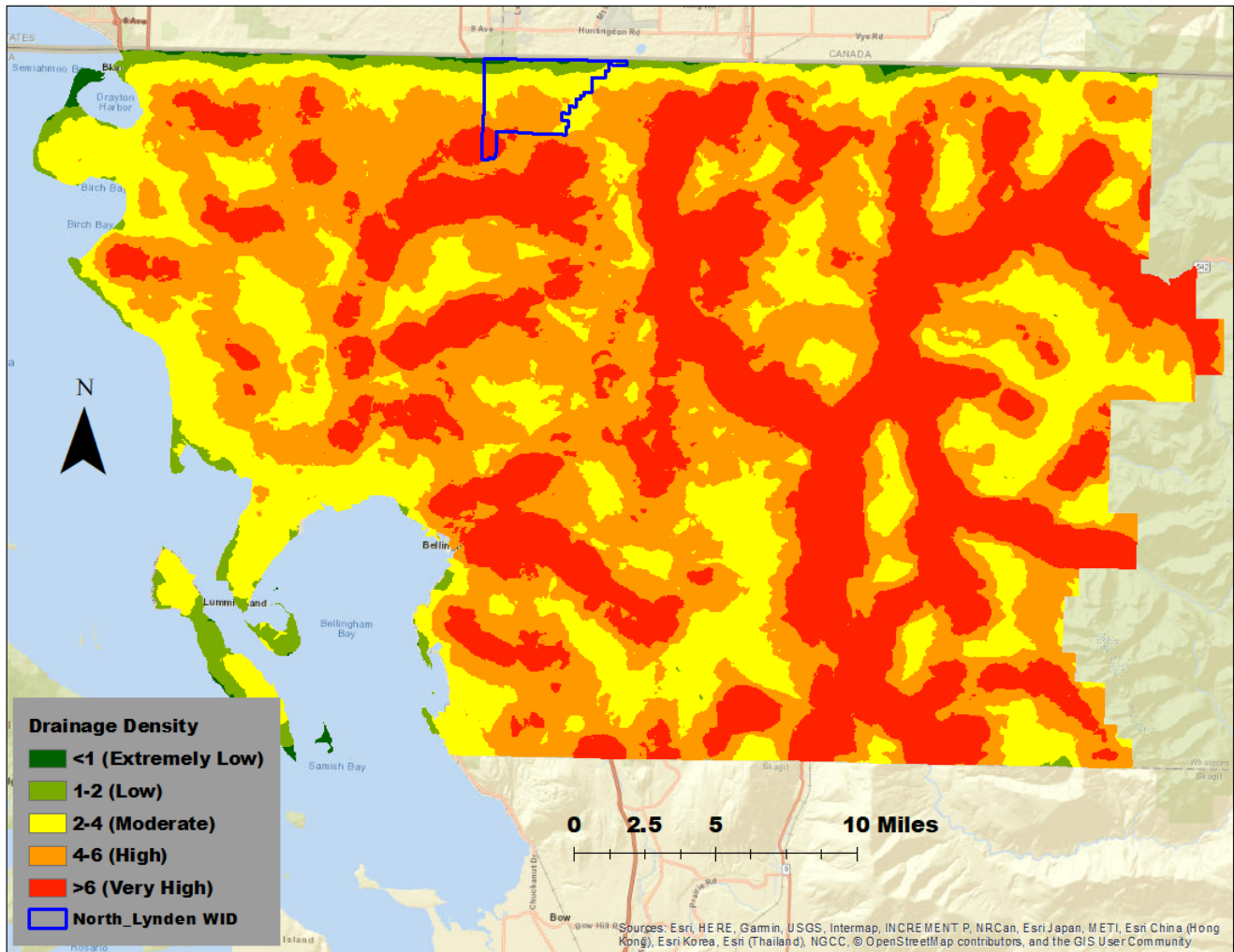


Figure 8. Map of Whatcom County showing Drainage Density derived from Digital Elevation Model.

Precipitation

Figure 9 illustrates the average annual precipitation from 1981 to 2010 in Whatcom County. The map unit is divided into five categories which are 31-35 inches (low potential), 36-50 inches (moderate potential), 61-80 inches (moderate potential), 81-100 inches (high potential), and 101-188 inches (high potential), respectively. The North Lynden WID received up to 51-80 inches of average annual precipitation within 1981-2010, and these values may be enough for adequate groundwater recharge. The distribution of rainfall in conjunction with slope gradient can easily affect the infiltration rate of runoff water hence, increases the possibility of groundwater recharge potential (Magesh *et al.*, 2012).

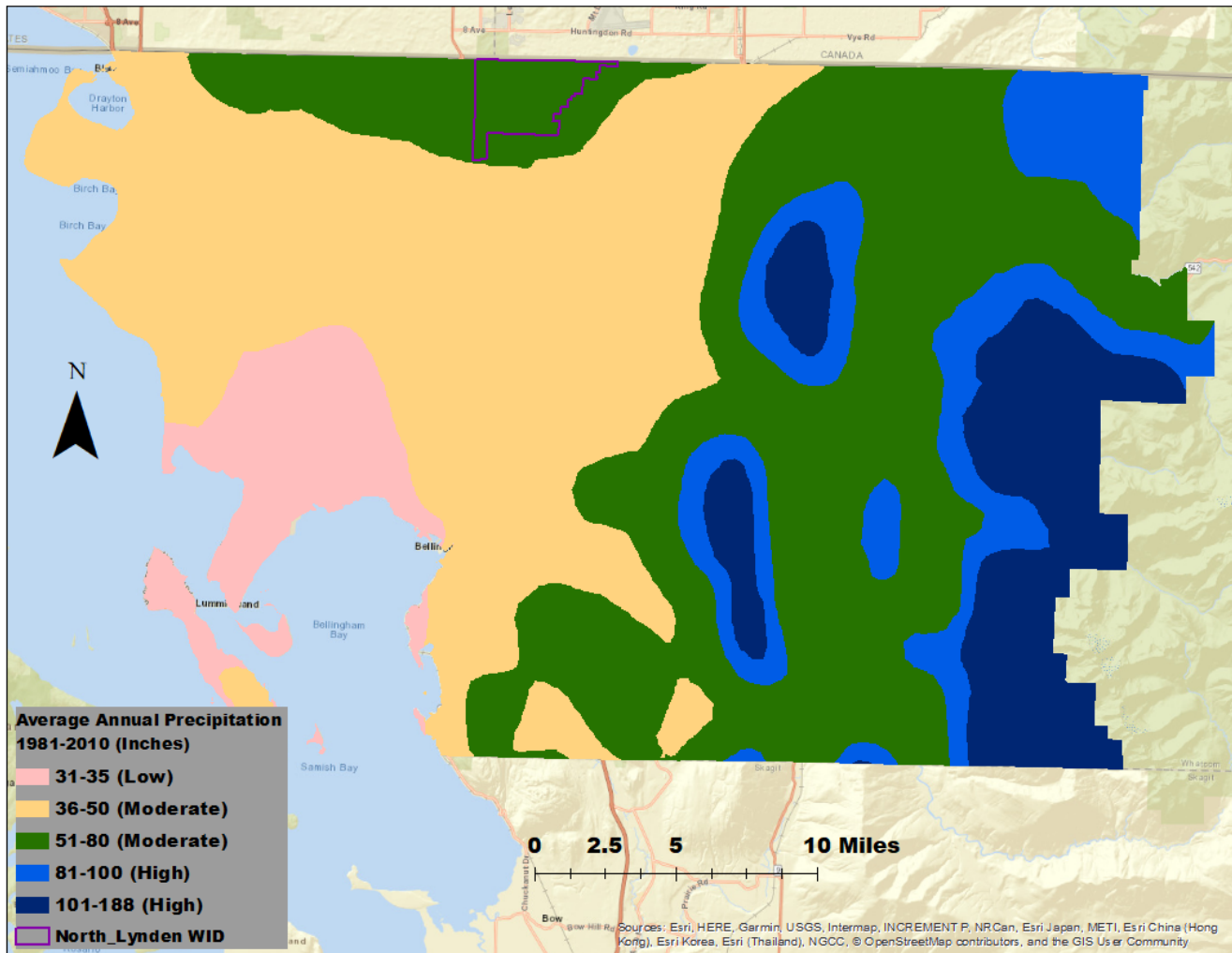


Figure 9. Map of Whatcom County showing the Average Annual Precipitation (1981-2010), obtained from USDA geospatial data gateway.

Soil

Soil type is an important component for the delineation of groundwater recharge potential zone (Pankaj *et al.*, 2016). According to the soil survey carried out by (Goldin, 1992), 192 different soil types were identified in the Whatcom County Area. Each soil types was assigned weightage based on their characteristics related to the groundwater recharge potential. Using soil properties such as drainage, permeability, slope percentage, effective rooting depth, height of water table, available water capacity and runoff rate, the soil types of Whatcom County were classified as good, moderate or poor recharge potential zones (Figure 10). Zooming in to the North Lynden WID there are 15 different soil types which falls within the moderate to good groundwater recharge potential zones, occupying ~ 6240 acres and ~5570 acres respectively.

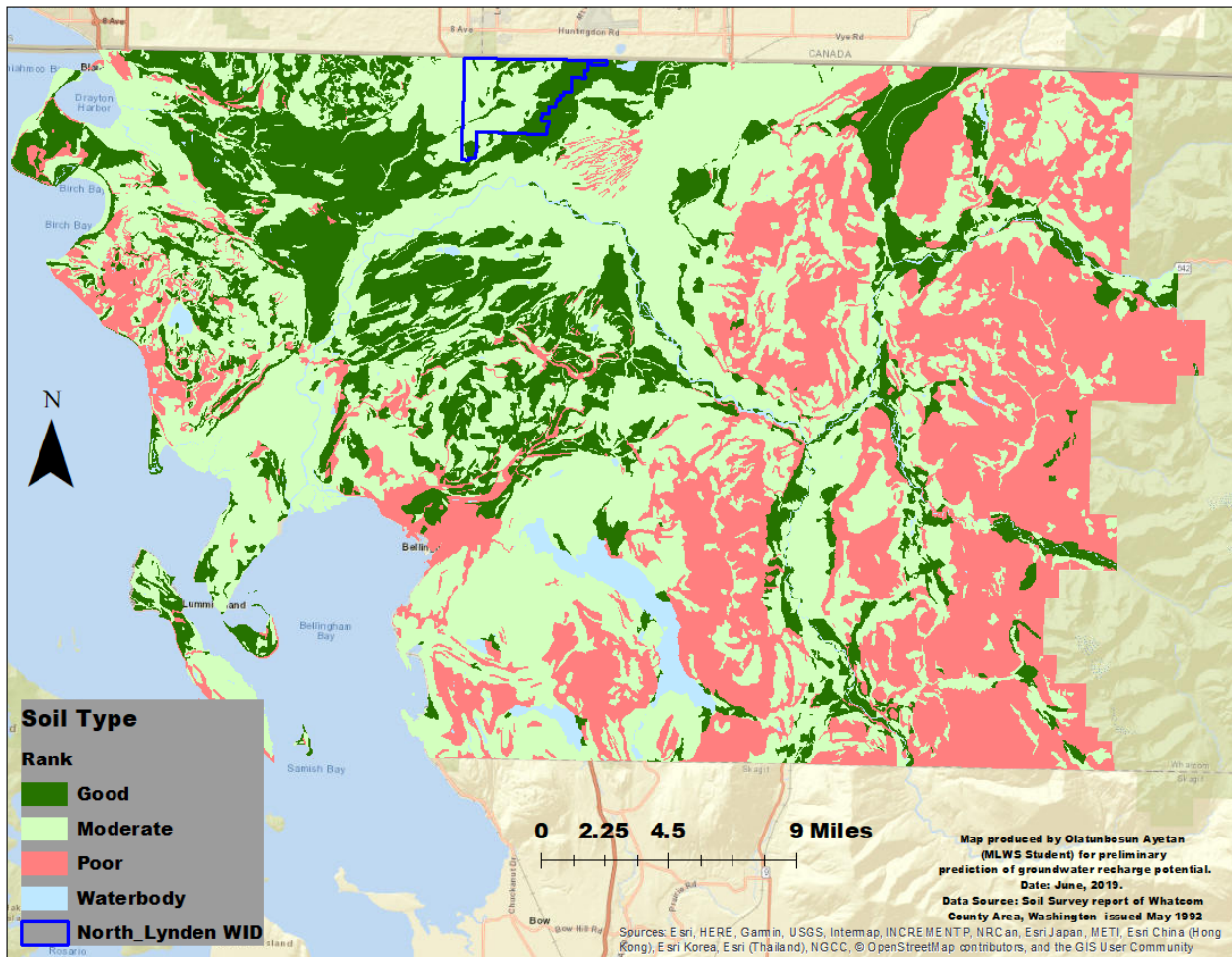


Figure 10. Map of Whatcom County showing the soil type ranking based on recharge potential. Derived from soil survey report of Whatcom County Area, Washington (May 1992).

Demarcation of Groundwater Recharge Potential Zone

The demarcation of groundwater recharge potential zones for the study area was made by overlaying weighted multi influencing factors and finally assigned different potential zones. The area was divided into five classes, namely low, moderately low, moderate, high and very high. The groundwater recharge potential map (Figure 11) demonstrates that ‘very high’ recharge potential zone is concentrated in the North Lynden WID, which could be due to the distribution of outwash plain and agricultural land use and land cover with high infiltration ability. Similar results were reported by Shankar and Mohan (2006); Magesh *et al.*, (2012), and this indicates that land use/land cover, soil type, and slope play a vital role in groundwater recharge.

Less than 0.01% and about 0.4% of the total area of the North Lynden falls under the ‘low and moderately low potential’ zones respectively, while 8.6% falls under ‘moderate’ zone, 48.3% falls under ‘high’ groundwater potential zone, and 42.7% of the study area falls under the ‘very high’ zone (Figure

12). Therefore, the cumulative effect of the multi-influencing factors that were weighted and overlaid in GIS platform revealed the mapping of groundwater potential zones in the study area.

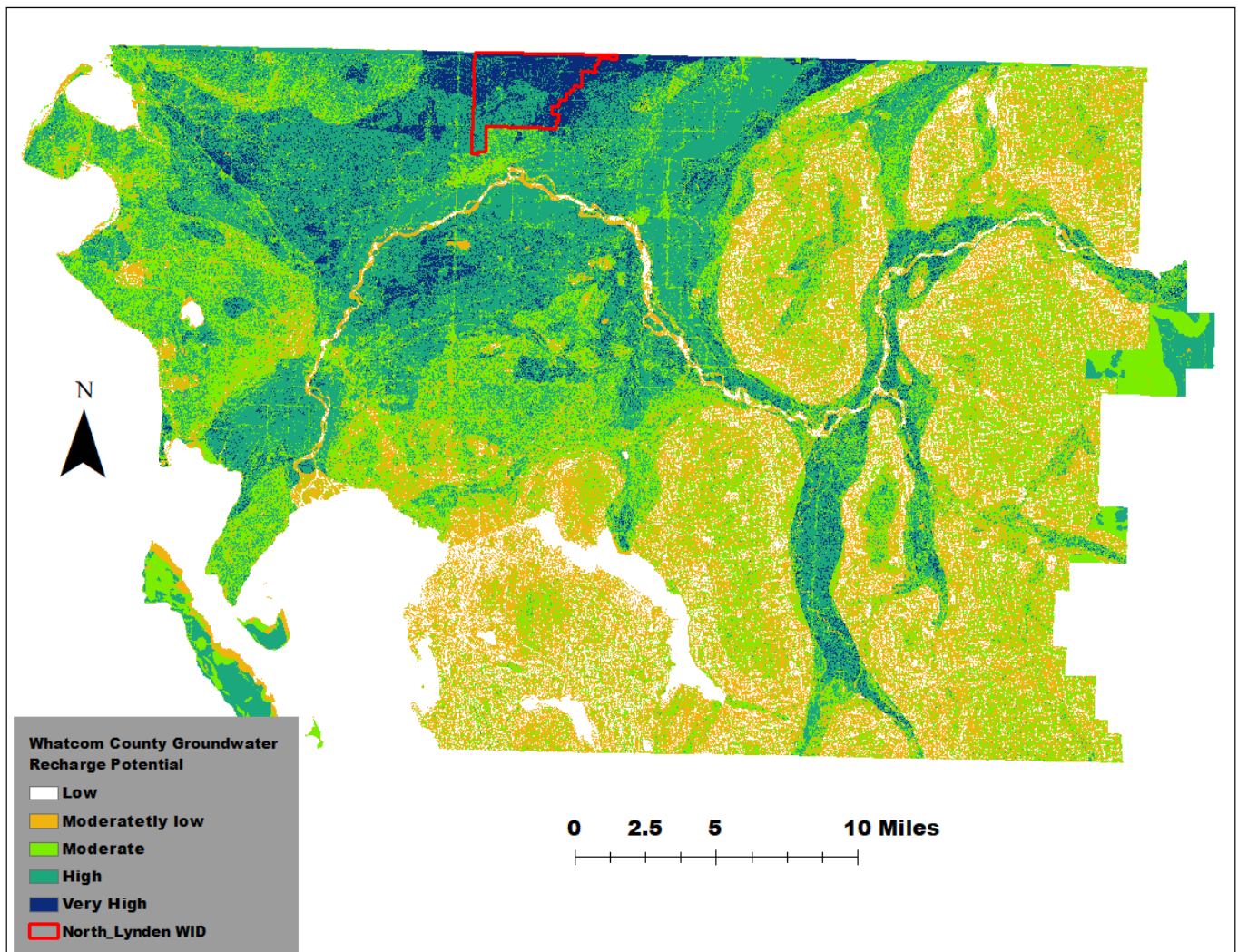


Figure 11. Map showing Whatcom County Groundwater Recharge Potential zones

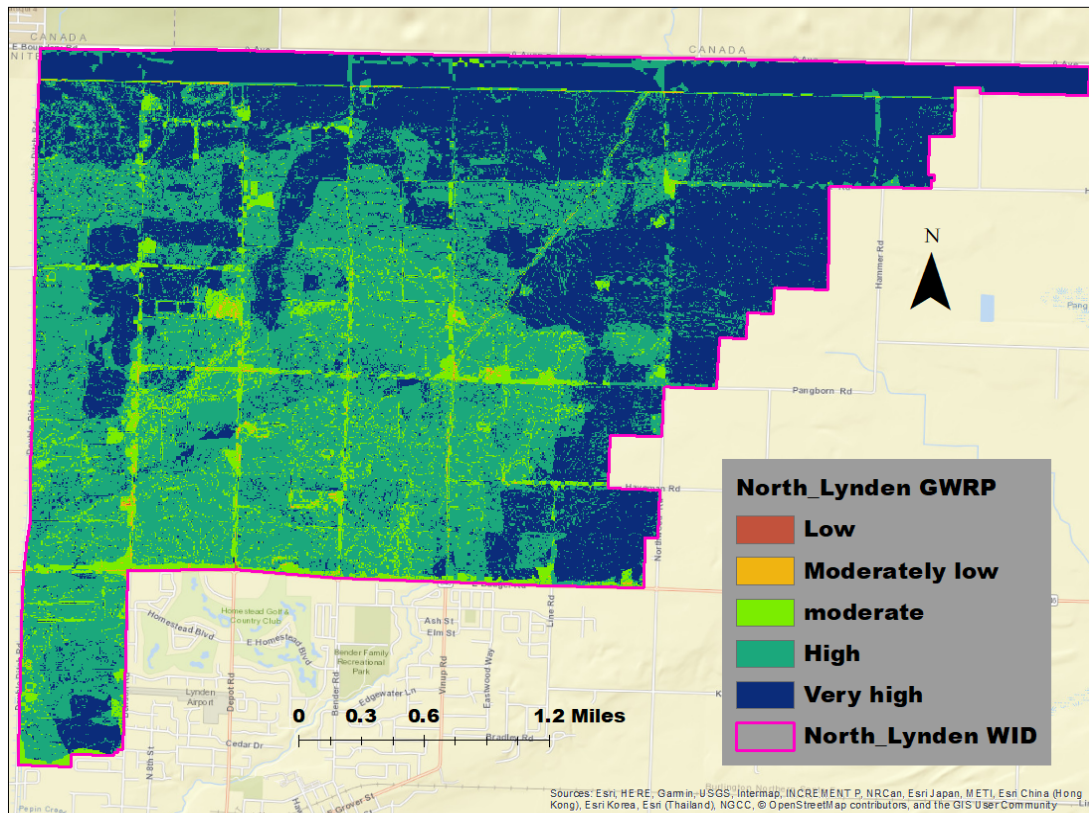


Figure 12. Map showing the North Lynden WID Groundwater Recharge Potential zones

4.2 Effects of Agricultural Activities on Groundwater Recharge Potential

4.2.1 Qualitative Soil Compaction Test using Penetrometer

There are several factors related to agricultural activities that could have site-specific or field-specific influences on groundwater recharge and they include, soil compaction, subsurface drainage and erosion. The compaction studies were a first qualitative assessment of how groundwater recharge potential might be affected under different crop types and it is suggested that more rigorous study be conducted in the future. Personal communication (Mackay, 2019) indicated that prior to the introduction of agriculture, the area between Lynden and the border were forested swamp. Some farmers in Whatcom County are installing pumped drainage for berry fields. The tile drains empty to a sump with a submersible pump and the drainage water is pumped into surface streams.

Table 4 below was constructed using data obtained from the penetrometer field test and the land cover and soil type were identified using the 'identify function' on North Lynden soil and crop distribution maps (see Appendix) in ArcGIS 10.6.1. In location 1, there is variation in the penetrometer readings across the different fields at 5cm and 20cm depth. The soil type, Clipper Silt Loam is very deep, poorly drained and is in outwash plains. Permeability is moderate in the upper part of the Clipper soil and rapid in the substratum (Goldin, 1992). The crop cover in location 1 is pasture and the penetration resistance of the soil is moderate, and this could be as a result of the management practices

such as running of tractor to cut pasture. Also, compaction can occur due to livestock trampling when feeding on the pasture.

Location 2 and 3 are corn-fields and the soil type (Fishtrap-muck) is very deep, very poorly drained and on outwash terraces. It has been artificially drained. Permeability is moderate, although effective rooting depth is limited by a seasonal high-water table (Goldin, 1992). The penetration resistance is moderate in the row and interrow.

The highest penetration resistance was recorded in the hay/grass field (location 5), exceeding 300psi, especially on the track. The high compaction level of location 5 could be because of the working of heavy machinery when cutting the grasses. The soil type is Hale silt loam, which is similar in description with soil in location 1 and 2.

The lowest penetration resistance was recorded in Berthusen Park (which is a disturbed mixed forest, including open area, fallen trees, Doug Fir, Big-leaf maple, sword ferns, Western hemlock, and Western red Cedar).

Table 4. Penetrometer field test results

Location	Site	Depth	Cone Index (PSI)	Compaction	Land Cover	Soil Type	
1	Field 1	5cm	200-300	Moderate	Pasture	Clipper Silt Loam, drained, 0 to 2 % slopes	
		15cm	250-300				
	Field 2 (Near Peat)	5cm	110-150				
		20cm	140-200				
	Field 3	5cm	50-120				
		20cm	140-200				
	Field	5cm	150-200				
		20cm	250-300				
2	Row	5cm	50-200	Moderate	Corn	Fishtrap muck, drained, 0 to 2 % slopes	
		20cm	150-200				
	Interrow	5cm	50-200				
		20cm	150-250				
3	Row	5cm	100-150	Moderate	Corn	Fishtrap muck, drained, 0 to 2 % slopes	
		20cm	150-200				
	Interrow	5cm	100-150				
		20cm	200-250				
4	Berthusen Park	0-5cm	0-50	Low	Disturbed	Laxton Loam, Edmonds Woodlyn loam and Tromp loam (0-2% slope)	
		20cm +	50-100		Mixed		
					Forest		
5	Random Points	5cm	110-200	High	Grass/Hay	Hale silt loam, drained, 0 to 2 % slopes	
		20cm	250-300+				
	Track	5cm	300				
		20cm	500+				
6	Row and Interrow	5cm	100-200	Moderate	Corn	Hale silt loam, drained, 0 to 2 % slopes	
		20cm	250				
		25+cm	Drops to 50				

5.0 CONCLUSION AND RECOMMENDATIONS

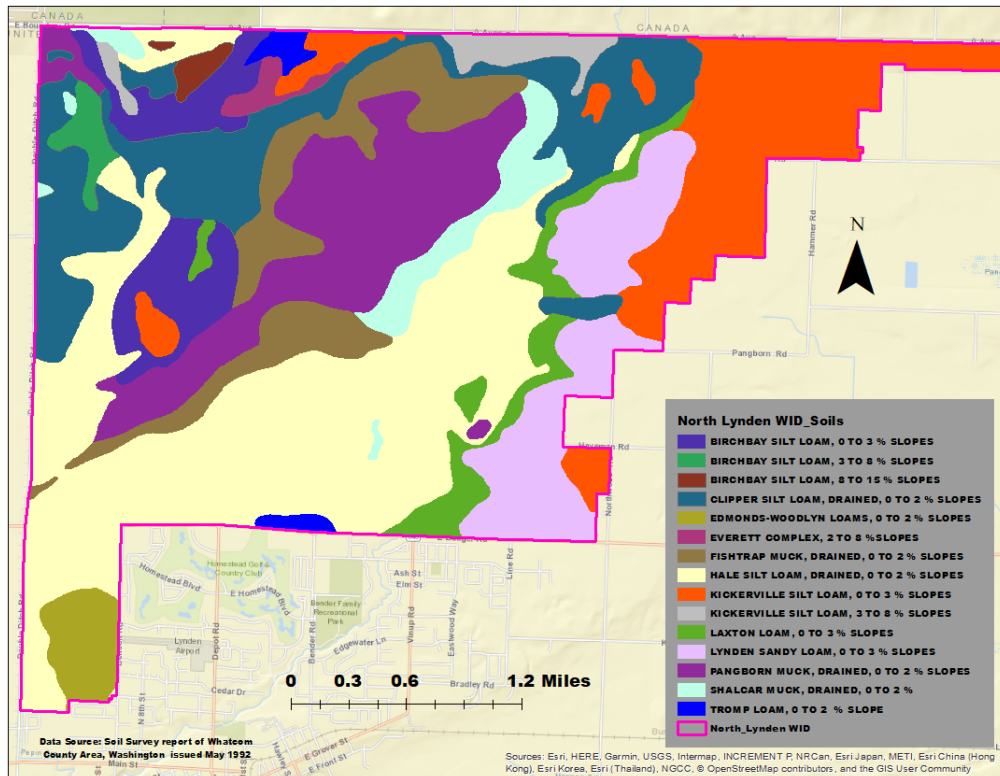
Delineation of groundwater recharge potential zones in the North Lynden WID, Whatcom County was conducted using GIS techniques that provided an effective methodology in the context of time, labour and cost. Seven thematic layers, namely, curvature, geology, soil type, slope, land use/land cover, drainage density and precipitation were prepared using digital terrain model, digital elevation model, topographic maps, and secondary data set, and integrated within GIS platform to generate groundwater recharge potential map of the area. The result shows that the study area was divided into five groundwater recharge zones, such as low (0.009% of the area), moderately low (0.40% of the area), moderate (8.56%), high (48.32%) and very high (42.71% of the study area). Results of this study reveal a significant groundwater recharge potential in North Lynden WID, which could be due to the geology, land curvature, soil type, drainage density, slope, land use/land cover and high precipitation in the region. The penetrometer field test qualitatively revealed that land cover and the required management practices in addition to the soil types can affect groundwater recharge potential.

The resultant suitability map and the methodology employed in this study will serve as a guideline for future water management projects. The methodology used here can be applied in other areas of the world experiencing water stress conditions with appropriate modifications. This study is very useful to the public and government sector to know the potential zone of groundwater recharge for sustainable management and utilization. The results indicate that application of GIS techniques for groundwater exploration can help to narrow down the target areas for conducting detailed hydrogeological surveys on the ground. The maps obtained by this method can be used by government and water policy decision-makers as a preliminary reference in selecting suitable sites for groundwater resources management, e.g., drilling new boreholes, stormwater attenuation, and green infrastructure.

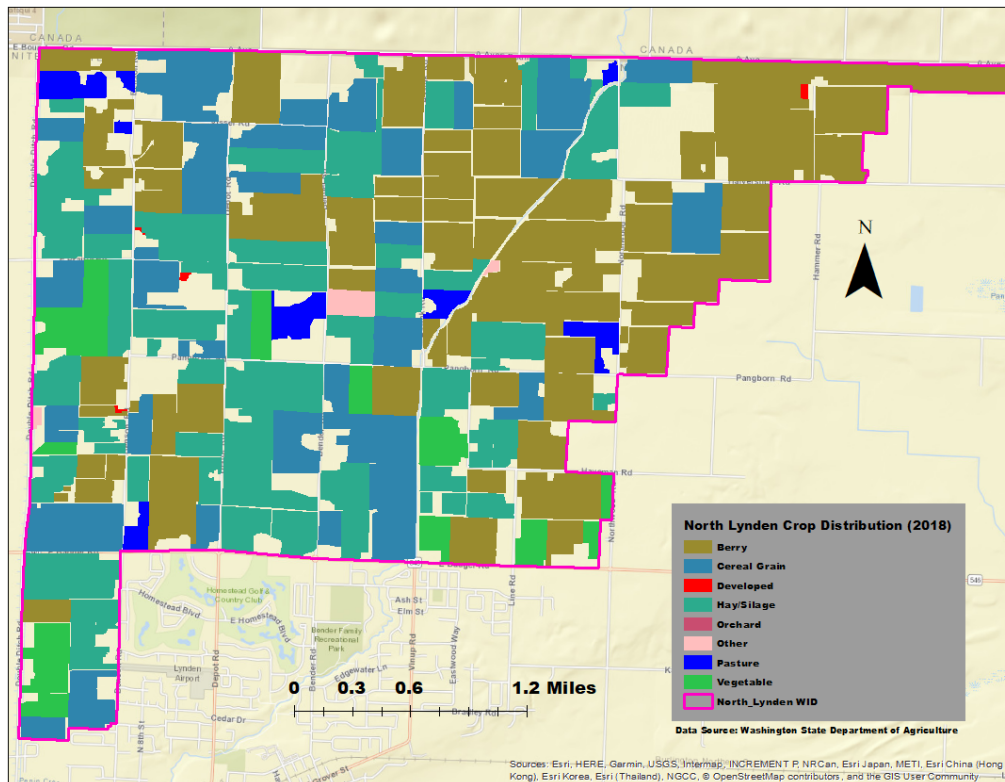
This is an empirical method for the exploration of groundwater potential zones using GIS techniques, and it succeeded in proposing potential sites for groundwater recharge zones. However, the results of this study can be enhanced by increasing the precision and spatial resolution of the data.

It can be recommended that the results of this investigation be reviewed by stakeholders and recommend additional concerns that may be addressed. The growers and stakeholders, including government officials should consider effects of land use on discharge and recharge dynamics. Also, growers need to assess management practices as they might affect groundwater recharge. Finally, the study should be expanded to include other environmental goods and services congruent with the public priorities.

APPENDIX



Appendix 1. Soil map of North Lynden WID



Appendix 2. Crop distribution maps of North Lynden WID

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REFERENCE

- Benedict, M. A., & McMahon, E. T. (2002). Green infrastructure: smart conservation for the 21st century. *Renewable resources journal*, 20(3), 12-17.
- Benyon, R. G., Theiveyanathan, S., & Doody, T. M. (2006). Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany*, 54(2), 181-192.
- Blainey, J. B., and J. D. Pelletier (2008), Infiltration on alluvial fans in arid environments: Influence of fan morphology, *J. Geophys. Res.*, 113, F03008, doi:10.1029/2007JF000792.
- Chachadi, A. G. (2015). New Indicator based method SALDIT for delineation of natural groundwater recharge areas. *Aquatic Procedia*, 4, 649-659.
- Duiker, S. W. (2002). Diagnosing soil compaction using a penetrometer (soil compaction tester). *Agronomy facts*, 63(4).
- Egoh, B., Rouget, M., Reyers, B., Knight, A. T., Cowling, R. M., van Jaarsveld, A. S., & Welz, A. (2007). Integrating ecosystem services into conservation assessments: a review. *Ecological Economics*, 63(4), 714-721.
- ESRI (2018). ArcGIS 10.6.1. ESRI (Environmental Systems Research Institute), Redlands
- Gendaszek, A. S. (2014). Hydrogeologic framework and groundwater/surface-water interactions of the South Fork Nooksack River basin, northwestern Washington (No. 2014-5221). US Geological Survey.
- Gnanachandrasamy, G., Zhou, Y., Bagyaraj, M., Venkatramanan, S., Ramkumar, T., & Wang, S. (2018). Remote sensing and GIS based groundwater potential zone mapping in Ariyalur District, Tamil Nadu. *Journal of the Geological Society of India*, 92(4), 484-490.
- Goldin, A. (1992). Soil Survey of Whatcom County Area, Washington. US Department of Agriculture, Soil Conservation Service.
- Gornitz, Vivien (ed.) (2009). *Encyclopedia of Paleoclimatology and Ancient Environments*. Springer: Dordrecht, p. 665.
- Heather Mackay Brown (PhD) (2019). Personal Communication. Director, FHB Consulting Services Inc. Lynden WA 98264, United States of America www.fhb3.com.
- Horton, R.E. (1945) Erosional development of streams and their drainage density: hydrophysical approach to quantitative geomorphology. *Geol. Soc. Amer. Bull.*, v.56, pp.275-370.
- Jodi DeJong-Hughes (2018). Soil Compaction. University of Minnesota Extension. © 2019 Regents of the University of Minnesota. <https://extension.umn.edu/soil-management-and-health/soil-compaction#sources-1200560>
- Lin, Jiajia; Compton, Jana; Baron, Jill; Clark, Chris; Schwede, Donna; Bittman, Shabtai; Hooper, David; Carey, Barb; Homann, Peter; Winter, Hanna; Kiffney, Peter; Embertson, Nichole; MacKay, Heather; Black, Robert; and Bahr, Gary (2018). "Nitrogen Inventory in the Nooksack-Fraser Transboundary Watershed". Salish Sea Ecosystem Conference. 485. <https://cedar.wvu.edu/sscc/2018sscc/allsessions/485>
- MacDonald, A. M., & Calow, R. C. (2009). Developing groundwater for secure rural water supplies in Africa. *Desalination*, 248(1-3), 546-556.
- Magesh, N. S., Chandrasekar, N., & Soundranayagam, J. P. (2012). Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geoscience Frontiers*, 3(2), 189-196.

- Millennium Ecosystem Assessment, (2005). Ecosystems and Human Well-being. Synthesis. Island Press, Washington DC, pp. 137.
- Naumann, Sandra, McKenna Davis, Timo Kaphengst, Mav Pieterse and Matt Rayment (2011): Design, implementation and cost elements of Green Infrastructure projects. Final report to the European Commission, DG Environment, Contract no. 070307/2010/577182/ETU/F.1, Ecologic institute and GHK Consulting.
- North Lynden Watershed Improvement District (NLWID), (2018). North Lynden Watershed Improvement District. 204 Hawley Street Lynden, WA 98264. <https://www.northlyndenwid.com/>
- Pankaj Kumar, Srikantha Herath, Ram Avtar, Kazuhiko Takeuchi (2016) Mapping of groundwater potential zones in Killinochi area, Sri Lanka, using GIS and remote sensing techniques. *Sustain. Water Resour. Managmt.* v.2, pp.419–430, DOI 10.1007/s40899-016-0072-5.
- Puget Sound Institute (2019). Nooksack Watershed. Encyclopedia of Puget Sound. (<https://www.eopugetsound.org/terms/113>).
- Rao, B.V., Briz-Kishore, B.H. (1991) A methodology for locating potential aquifers in a typical semi-arid region in India using resistivity and hydrogeologic parameters. *Geoexploration*, v.27, pp.55–64.
- Roy, D., Venema, H. D., & McCandless, M. (2011). Ecological Goods and Services: A Review of Best Practice in Policy and Programming. International Institut for Sustainable Development.
- Shankar, M. R., & Mohan, G. (2006). Assessment of the groundwater potential and quality in Bhatsa and Kalu river basins of Thane district, western Deccan Volcanic Province of India. *Environmental Geology*, 49(7), 990-998.
- Singh, A., Panda, S. N., Kumar, K. S., & Sharma, C. S. (2013). Artificial groundwater recharge zones mapping using remote sensing and GIS: a case study in Indian Punjab. *Environmental management*, 52(1), 61-71.
- Whatcom Conservation District, (2009). North Lynden Watershed Improvement District. Drainage and Fish Habitat Management Plan. Published with support from the Centennial Clean Water Fund under the authority of the WA State Dept. of Ecology. https://whatcomcd.org/sites/default/files/ag_drainage/dmps/North%20Lynden%20WID%20Draft%20Drainage%20Mgt%20Guide.pdf
- Yeh, H. F., Cheng, Y. S., Lin, H. I., & Lee, C. H. (2016). Mapping groundwater recharge potential zone using a GIS approach in Hualian River, Taiwan. *Sustainable Environment Research*, 26(1), 33-43.