Forest Road Sedimentation

How do roads affect sedimentation?

- Impervious surfaces will create more runoff volume and at a faster delivery rate to watercourse.

- Non-impervious surfaces (forest roads) still facilitate the delivery and volume due to low absorption/percolation of the forest road.

- Non-maintained, poorly designed, or abandoned forest roads not only facilitate the above problems, the rate of erosion and sediment input into the watercourse drastically increases.

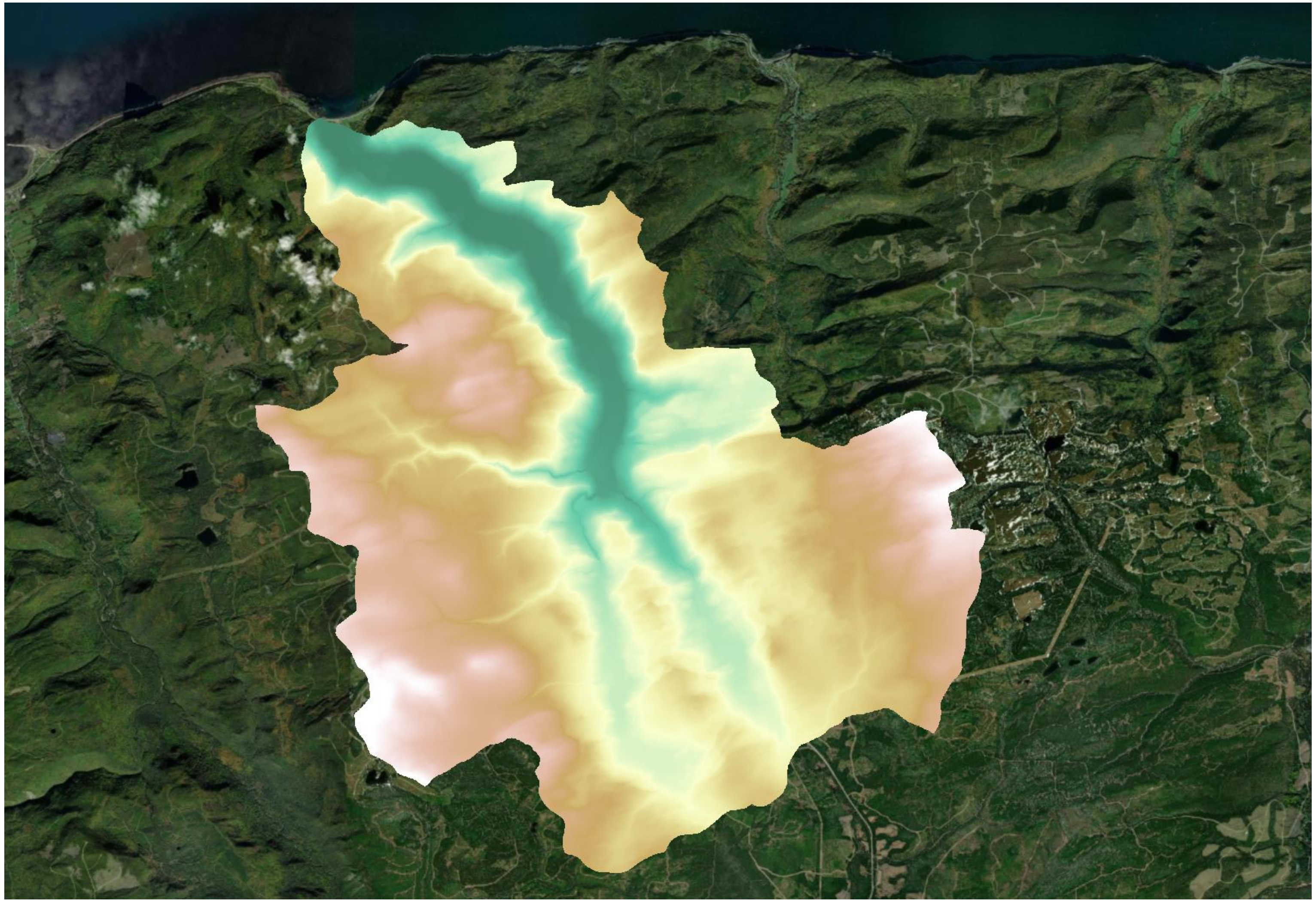
(Poesen et al., 2003; Cocker, 2007; Ferencevic & Ashmore, 2012; Katz et al., 2014)

Forest Road Sedimentation

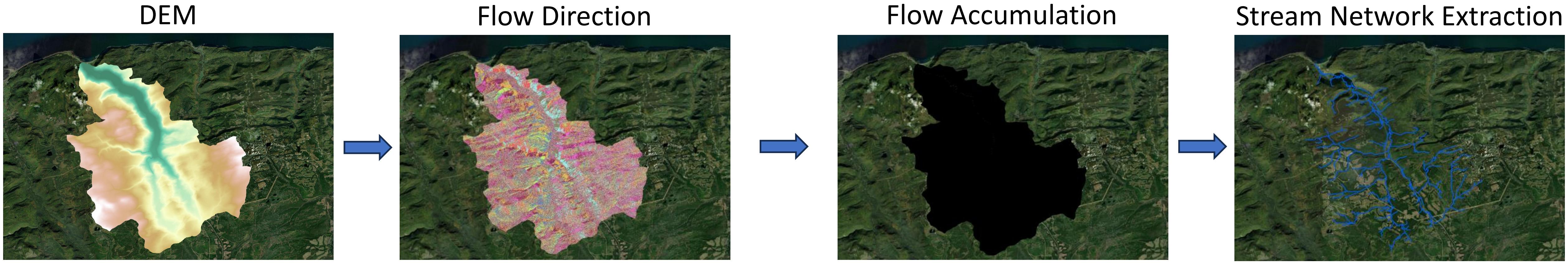
How can we identify areas of erosion risk/roadside runoff at a watershed scale?

- Using high resolution LiDAR DEM that is broadly available.
- Extracting landscape characteristics and drainage networks from the DEM.
- Creating models around the extracted terrain features and flow modelling to determine areas of concern.

Study Area: Anse Pleureuse, Rivière de l’
94.55 sq. km



Methodology



DEM

Flow Direction

Flow Accumulation

Stream Network Extraction

Workflow for Stream Power Index

Stream Power is the measure of the total energy of a hydrological channel which relates to sediment transport and erosion potential. Total stream power can be interrupted as Omega= pgQS. Where omega is stream power, p as density of water (1000 kg/m3), g is the acceleration due to gravity constant (9/8 m/s2), Q is discharge (m3/s), and S being the channel slope.

How can we calculate Q if we don’t have field data?

Workflow for Stream Power Index

How can we calculate Q if we don’t have field data?

The limiting factor in this equation that can’t be directly extracted from the LiDAR DEM is Q, channel discharge. This can be solved by one of two approaches:

1. Using Moore et al., (1991) methodology, stream power can be calculated using a relative stream power index, which is directly related to total stream power. The caveat is that discharge is proportional to the upslope contributing area. The index of the equation is as follows:
$RSP=Aspx \tan (B)$.

Where As is the upslope contributing area, B is the slope gradient, p is the exponent that determines the location specific relation between upslope contributing area and discharge.

2. Using frameworks like Gleason & Durand. (2020), McKean et al., (2009), and Dilts et al., (2010), the user can use flood modeling to estimate discharge and use that data to represent Q in the total stream power equation.

Proof of Concept

Steps:

1. Merge and hydro condition LiDAR DEM
2. Extracted road and stream data via LiDAR DEM.
3. Identification of stream road crossings.
4. Digitization of culvert, extraction of slope, length.
5. Stream power index applied to 300m buffer around the crossing.
6. Database of all stream-road crossings and relative stream power indices.
7. Analysis of erosion risk in non-stream-road crossings (Agricultural fields, clear cuts, etc…).

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Step 4

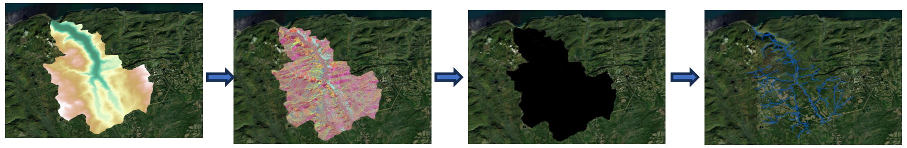
Step 5

Step 6

Step 3

Step 1

Hydro condition and stream extraction



Step 2

Steps:

Proof of Concept

1. Merge and hydro condition LiDAR DEM
2. Extracted road and stream data via LiDAR DEM.
3. Identification of stream road crossings.
4. Digitization of culvert, extraction of slope, length.
5. Stream power index applied to 300m buffer around the crossing.
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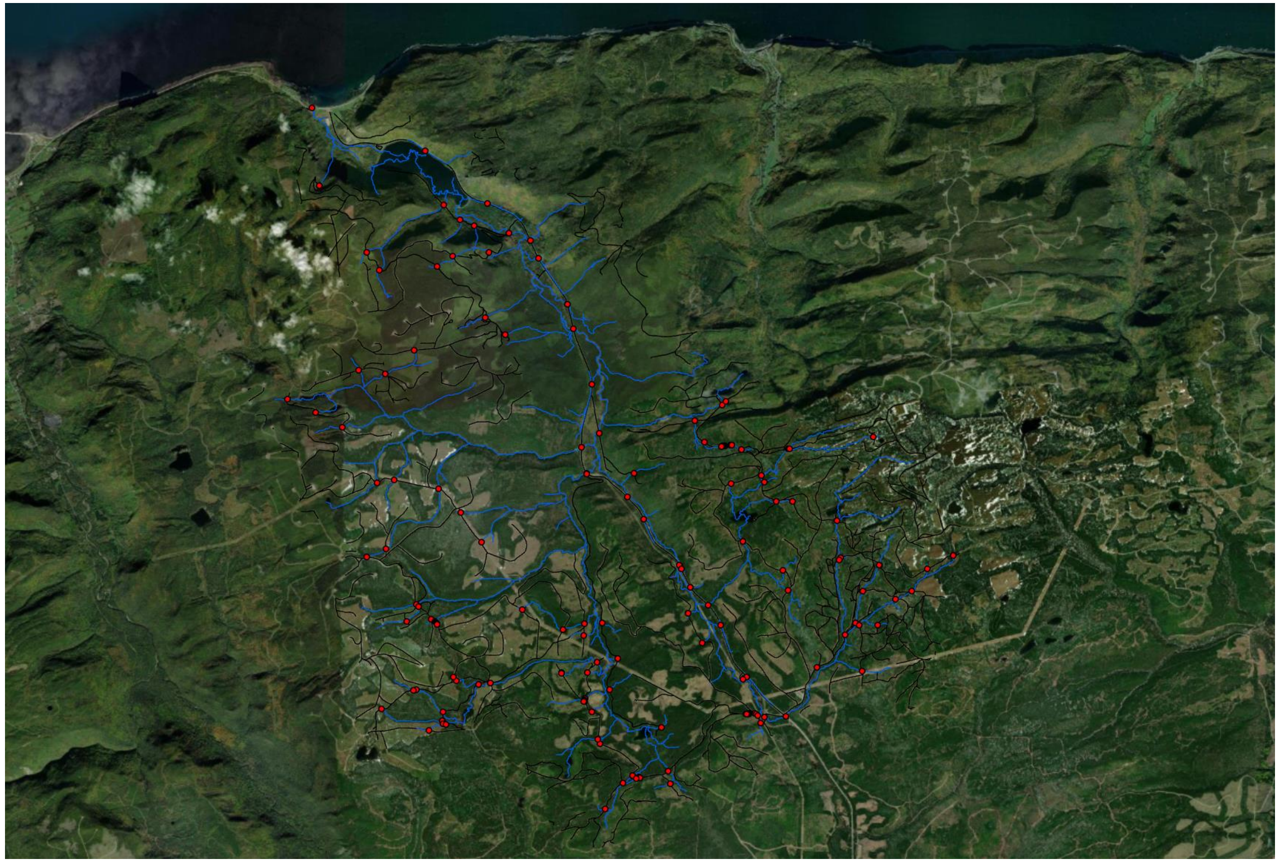
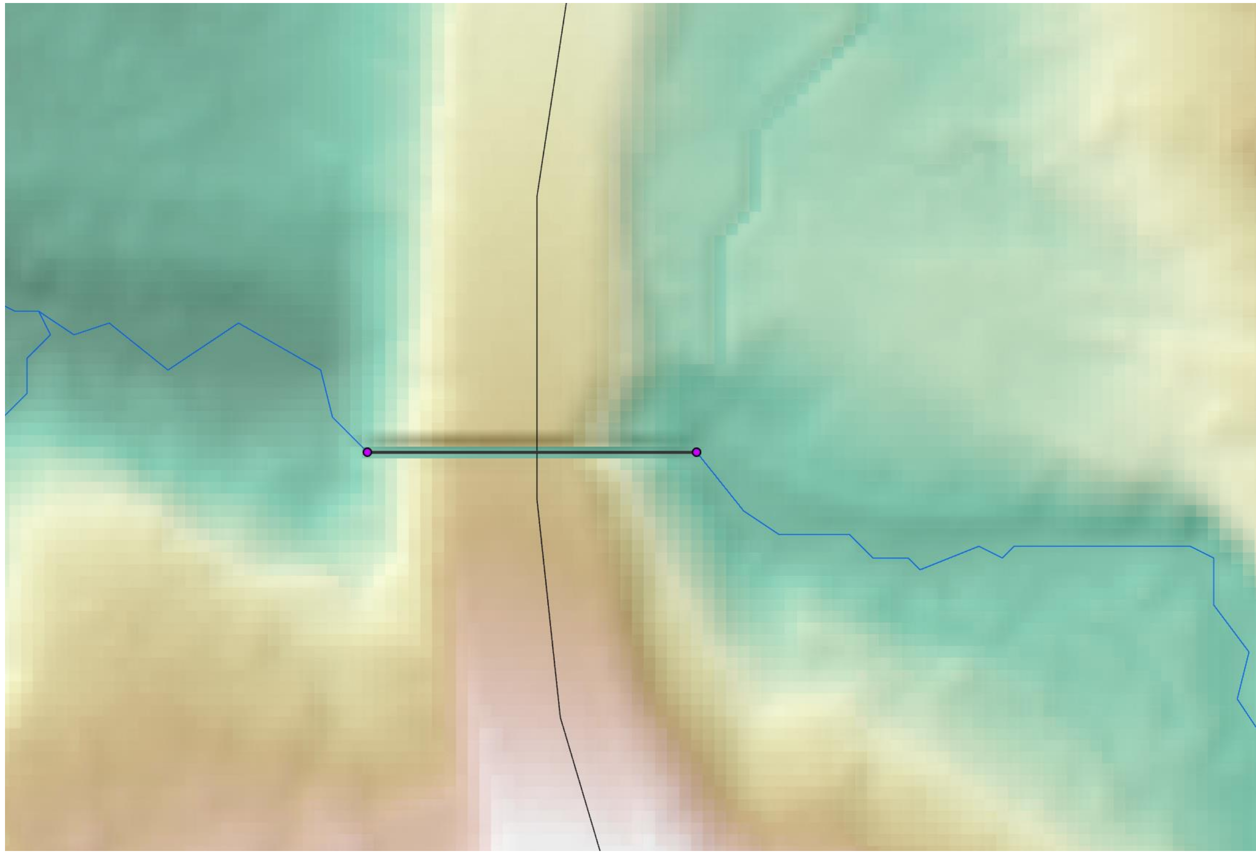
Step 5

Step 6

Step 3



Step 4



Steps:

Proof of Concept

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3. Identification of stream road crossings.
4. Digitization of culvert, extraction of slope, length.
5. Stream power index applied to 300m buffer around the crossing.

Step 5

Stream Power Index Scale

- 🟩 Low
- 🟨 Moderate
- 🟧 High
- 🟥 Severe

Does scale matter?

Stream Power Index values are relative to scale, so the values reflect the contributing area, hence the equation:

$$\Omega = \rho g Q S$$

SPI at 94.55 sq. km (watershed-level index)
Peak Index Value: 10,154,110

SPI at 1.8 sq. km(local scale)
Peak Index Value: 13,288,792

While they look similar, the local SPI has a higher peak index value, meaning that depending on the scale, the decision to classify it is erosion prone is spatially dependent.

Choosing what spatial scale to use

1. Stream Power is a good indicator of river dynamics that can tell us areas in which the stream is <u>**capable**</u> of to transport sediments.

2. Watershed scale analysis identifies the most vulnerable areas to fluvial processes.

3. We can find the difference between the watershed scale SPI and the local SPI to extract areas where there are drastic changes in stream power. This could be in areas where the terrain funnels the flow or disperses the stream energy through flood plains. This can be expressed as: $\Delta\omega = \omega_{local} - \omega_{upstream}$

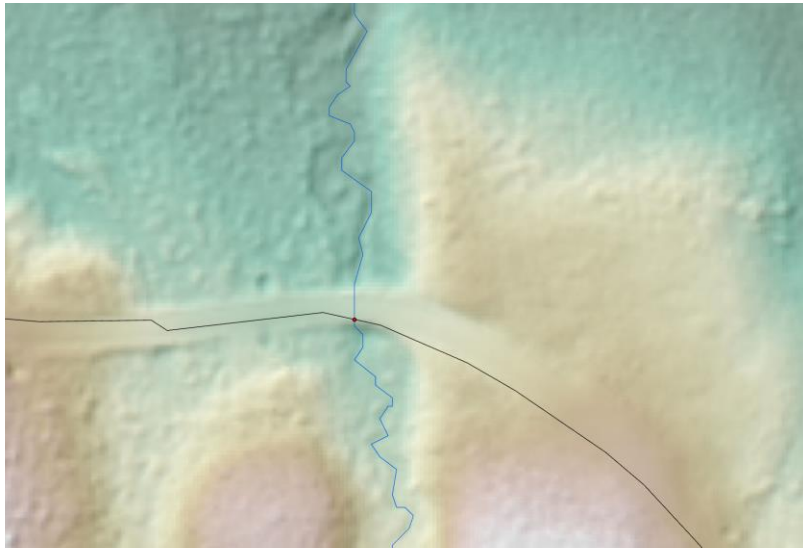
What to do after you identify high SPI areas

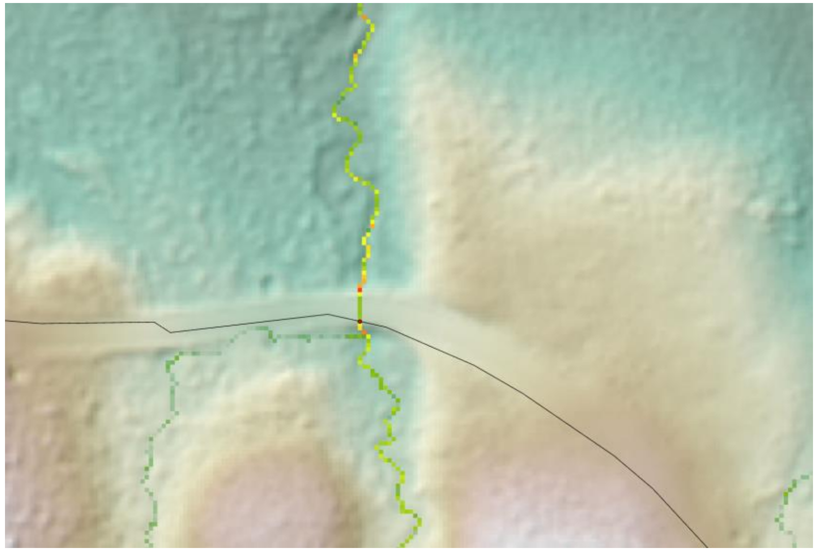
1. Locate crossings and forest roads that have high SPI within 300 m up and downstream of the crossing.

2. If the location has high SPI, extract profile curvature and drainage lines to identify specific areas where high SPI and high-profile curvature converge.

3. Assign point values based on priority or risk and add the SPI to the road embankment (profile curvature).

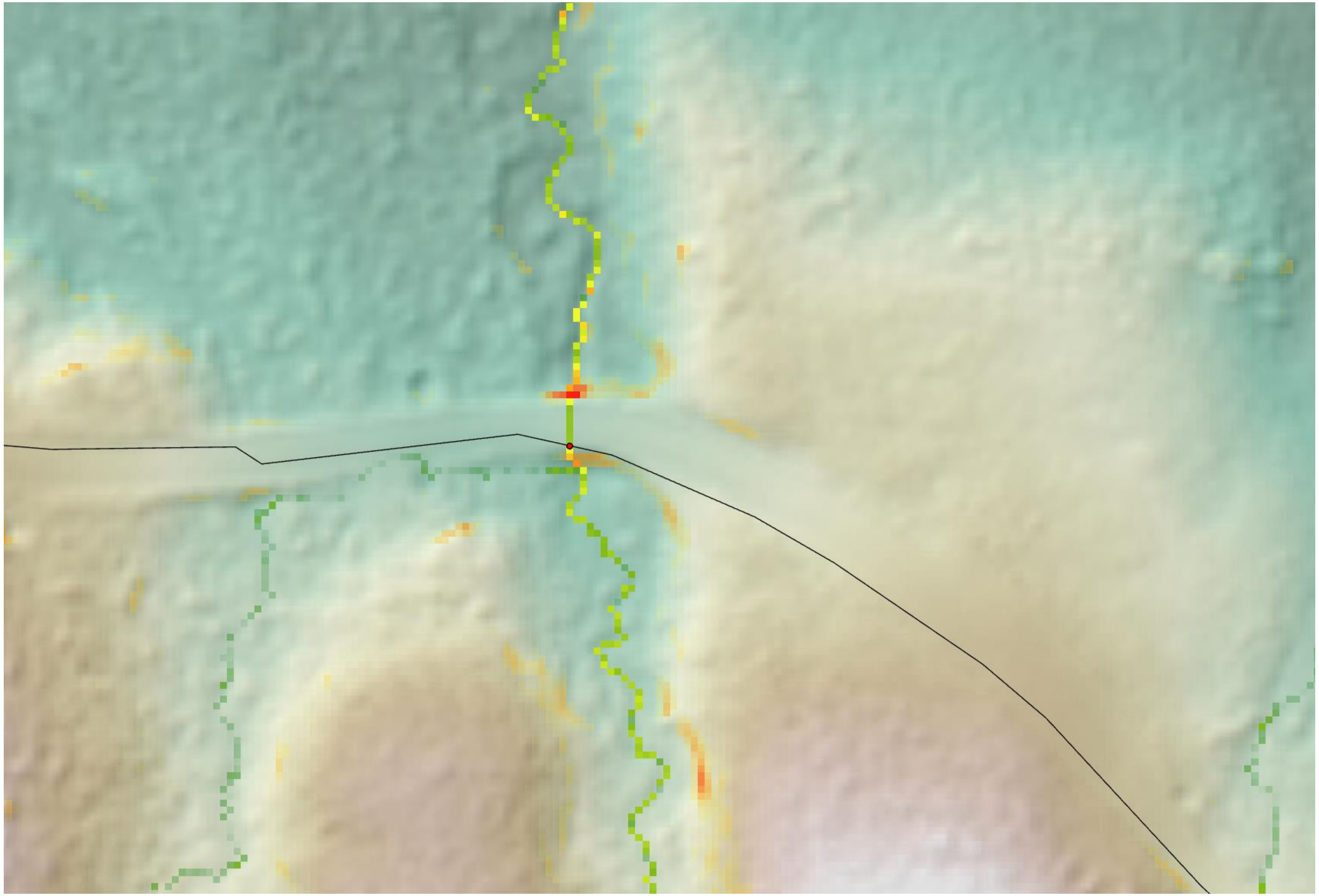
Example


DEM


SPI

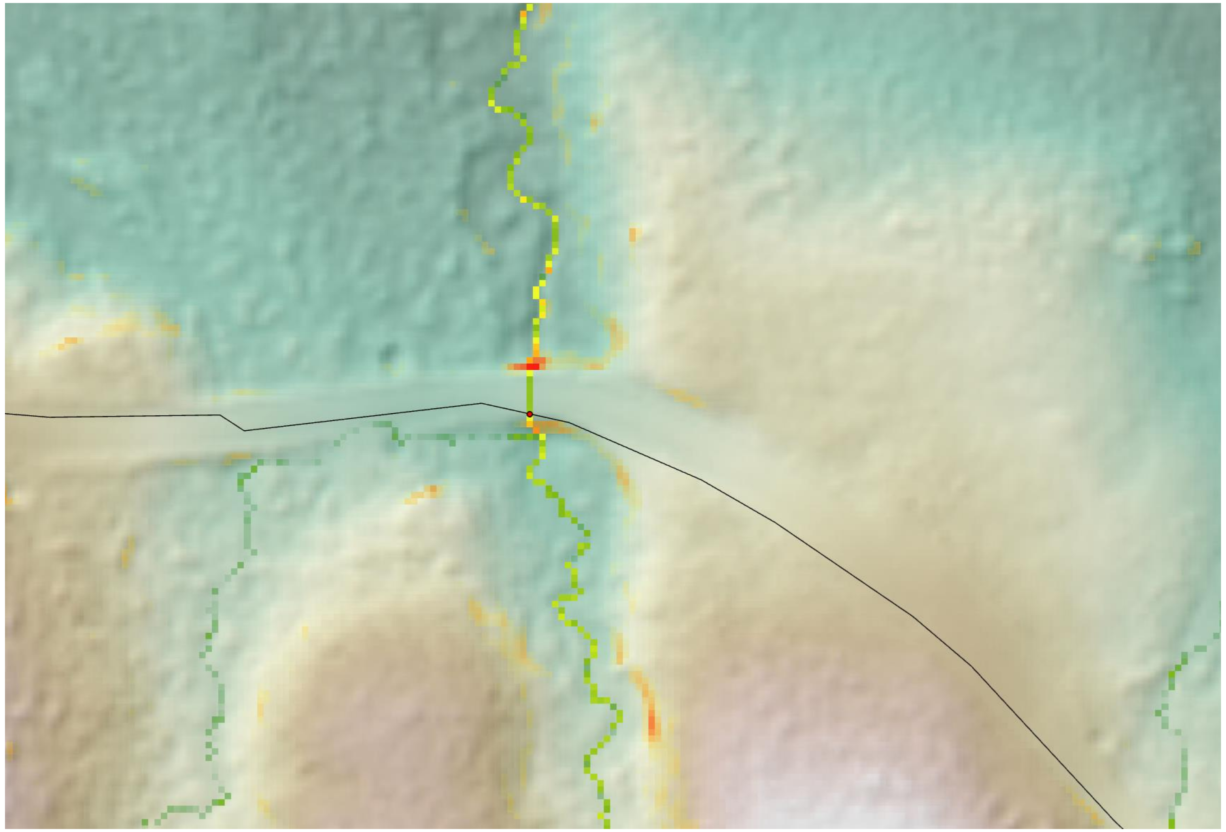

High degree slope areas

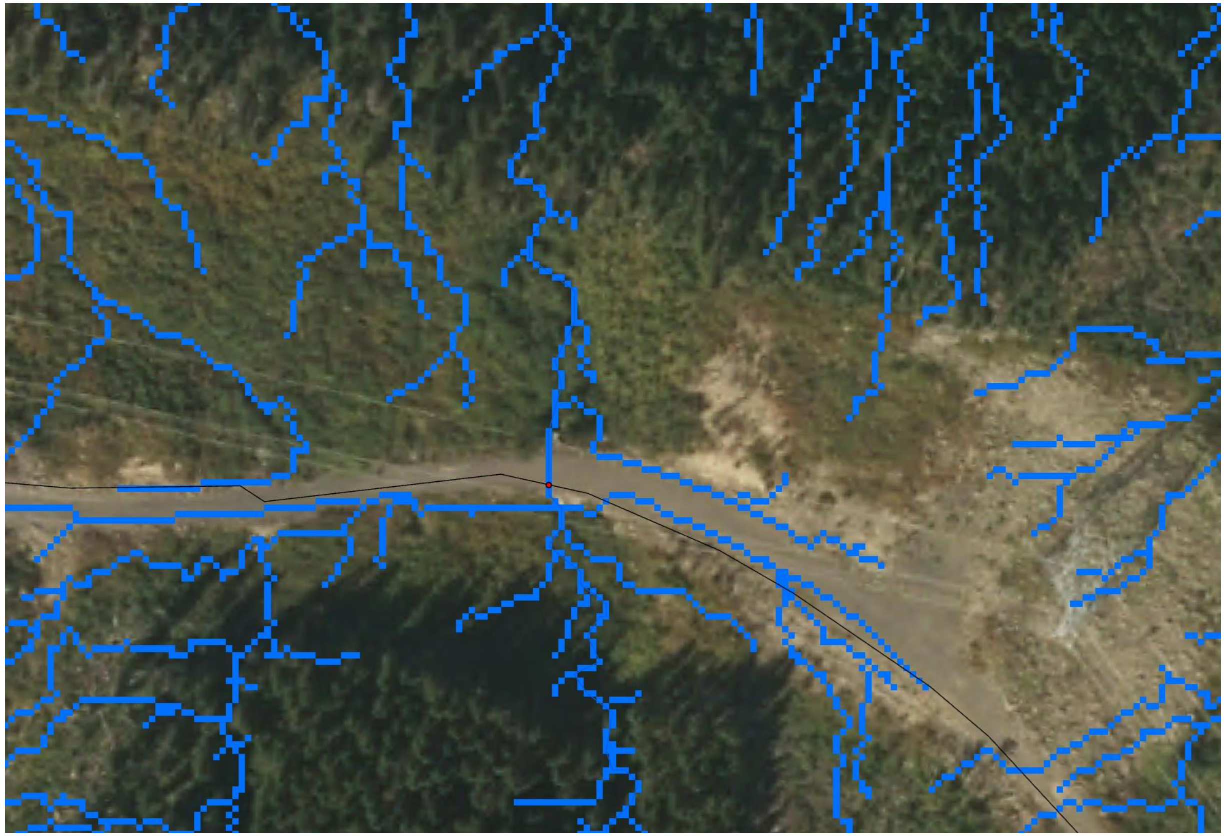
Combined
SPI + Slope around road



What can we extract from this?

1. Higher SPI downstream, than upstream. This suggests that the culvert has a high slope or elevation drop.
2. East road embankments on the up and downstream side have excessive slope leading to the high SPI areas, indicating high sediment deposit.
3. When overlayed with drainage lines and slope, it is easier to tell where the sediment is being carried.





Can you verify extracted findings without a field survey?

1.

If our calculated SPI is correct, where SPI is significantly lower upstream and higher downstream, the instream structure should have a higher slope to contribute to that increased SPI.

Upstream elevation: 458.03
Downstream elevation: 457.64
Elevation difference: 0.39 meters
Length of culvert: 12 m
Slope: 3.25%

Digitization of the culvert using methods from Arsenault et al., 2022 shows a higher than standard slope, which could result in the higher SPI observed downstream.

2.

Find evidence from orthophotography or other landscape visuals/characteristics.

The Universal Soil Loss Equation (USLE)

$$A = RKLSCP$$

Where:

A= mean annual soil loss

R= Rainfall Erosivity Factor

K= Soil Erodibility Factor

L= Slope Length Factor

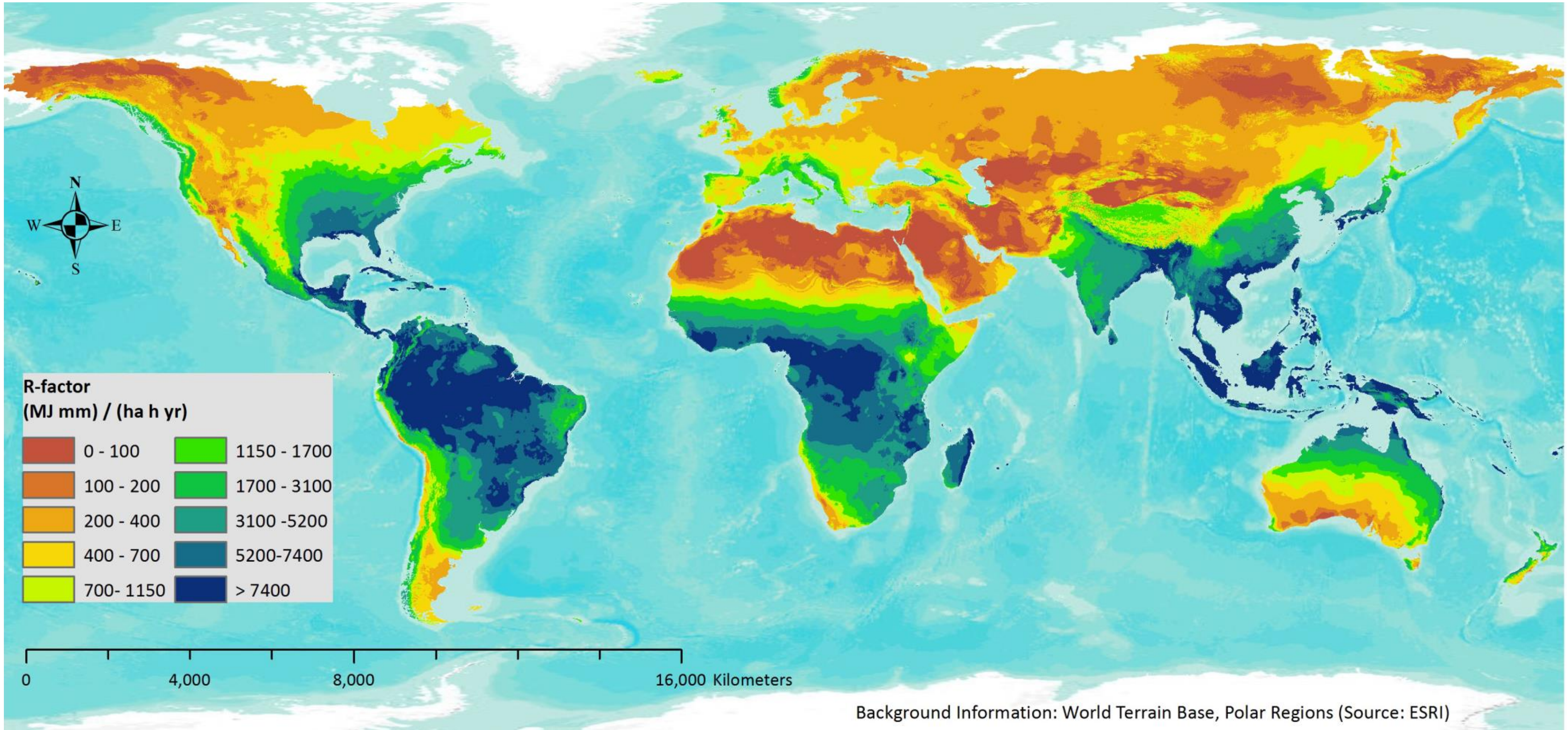
S= Slope Steepness Factor

C= Crop Management Factor

P= Erosion Control Practice Factor

A= **R**KLSCP
R= Rainfall Erosivity Factor

Global Rainfall Erosivity (ESDAC)



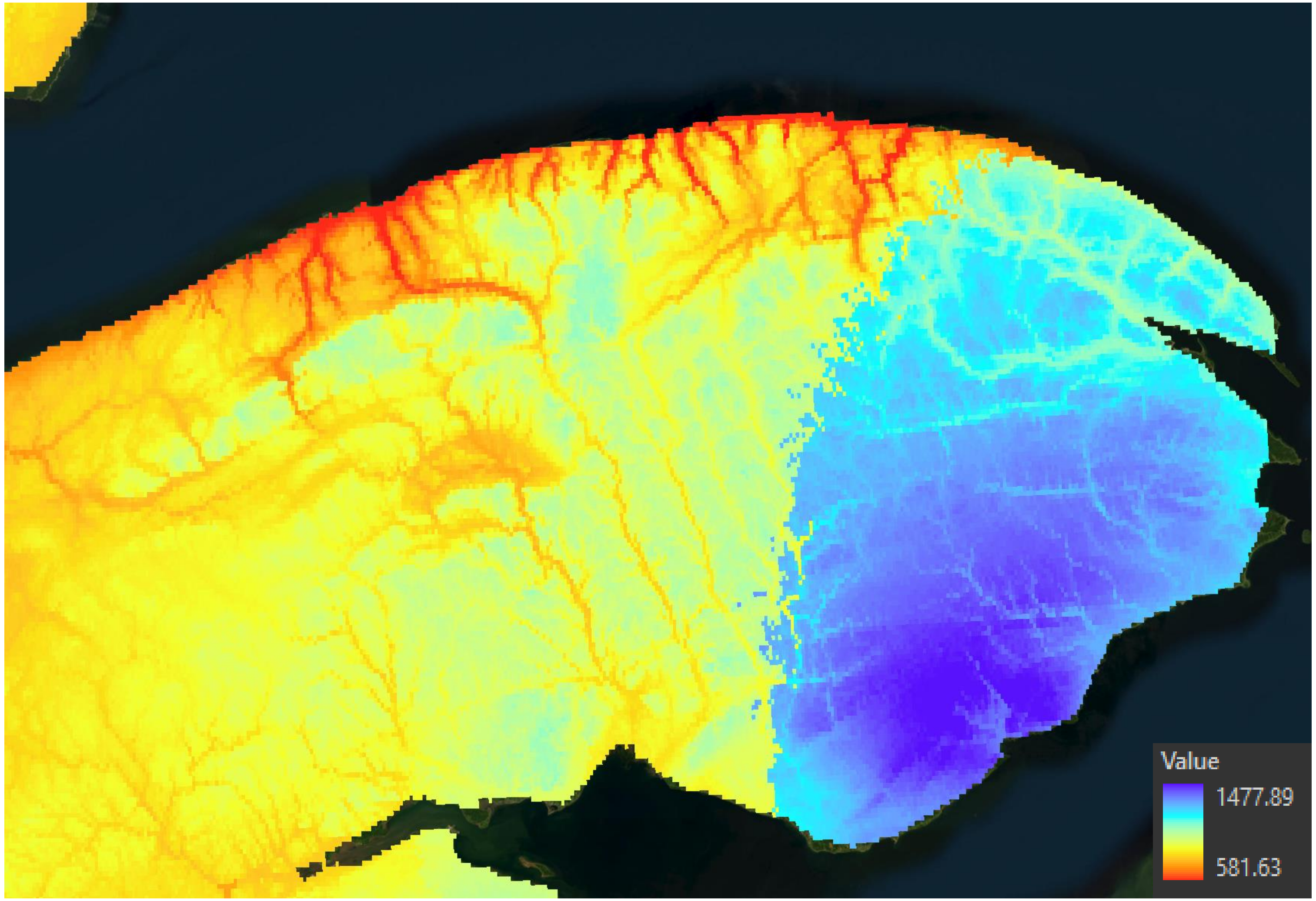
Background Information: World Terrain Base, Polar Regions (Source: ESRI)

Pixel Size: 30 arc-seconds
Time Range: 40 years
Measurement Unit: MJ mm ha^{-1} h^{-1} yr^{-1}

Fischer, G., F. Nachtergaele, S. Prieler, H.T. van Velthuizen, L. Verelst, D. Wiberg, 2008. *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. IIASA, Laxenburg, Austria and FAO,

A= **R**KLSCP
R= Rainfall Erosivity Factor

Rainfall Erosivity in the Gaspe Peninsula



Erosivity is the combination of two rainfall characteristics: kinetic energy and the maximum 30-minute intensity (Kirkby & Morgan, 1980).

Rain Erosivity can be expressed as a factor

$$R_j = E_j \times I_{j30} = \sum_{i=1}^{T_i} (e_i P_{ji}) \times I_{j30}$$

Where:

E_j is kinetic energy (MJ/mm)

I_{j30} is the maximum 30-min rainfall intensity (mm/h)

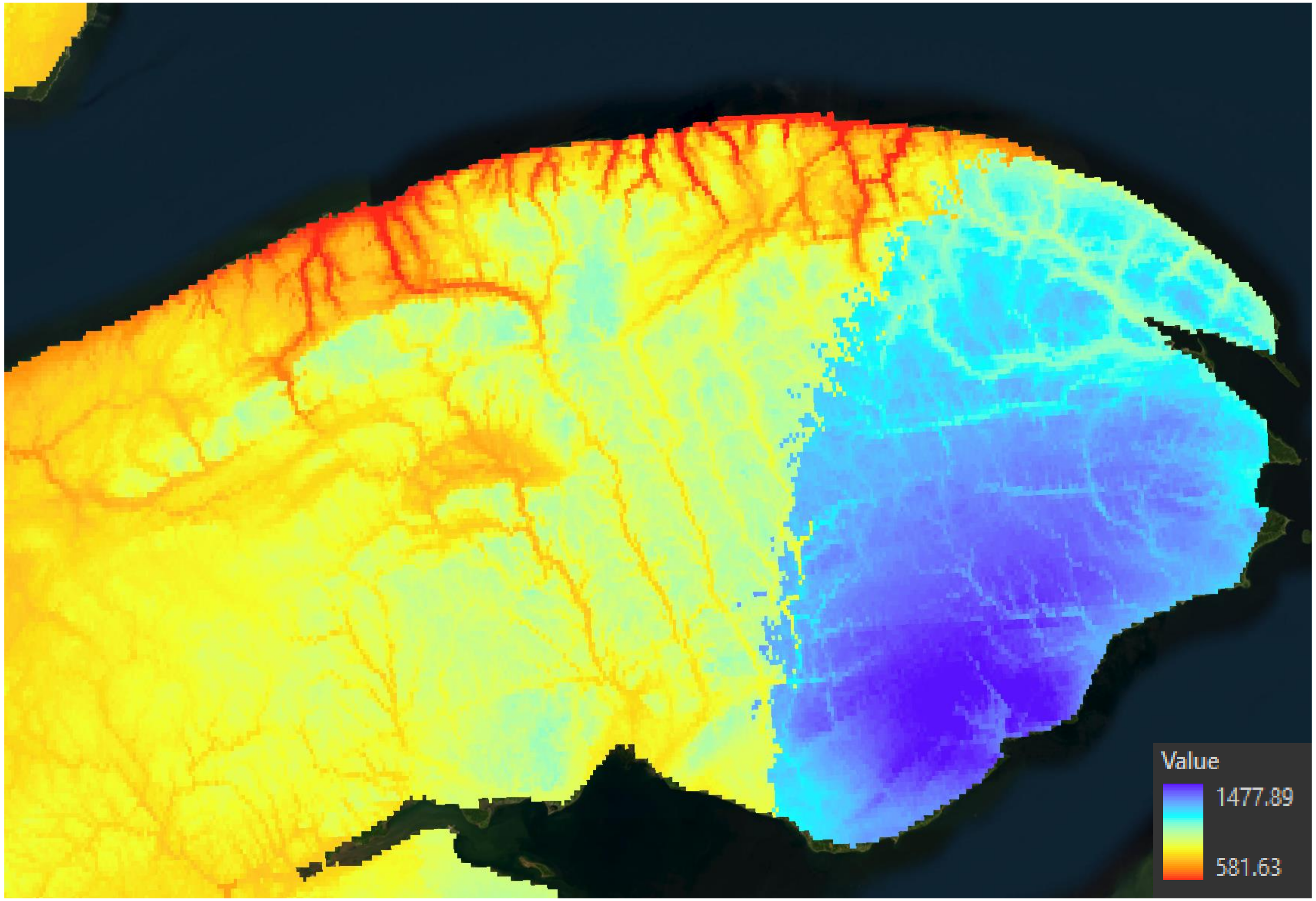
E_i is unitary kinetic energy (MJ/mm*ha)

P_{ji} is rainfall amount (mm)

T_i is total rainfall duration

A= **R**KLSCP
R= Rainfall Erosivity Factor

Rainfall Erosivity in the Gaspe Peninsula



$$R_j = E_j \times I_{j30} = \sum_{i=1}^{T_i} (e_i P_{ji}) \times I_{j30}$$

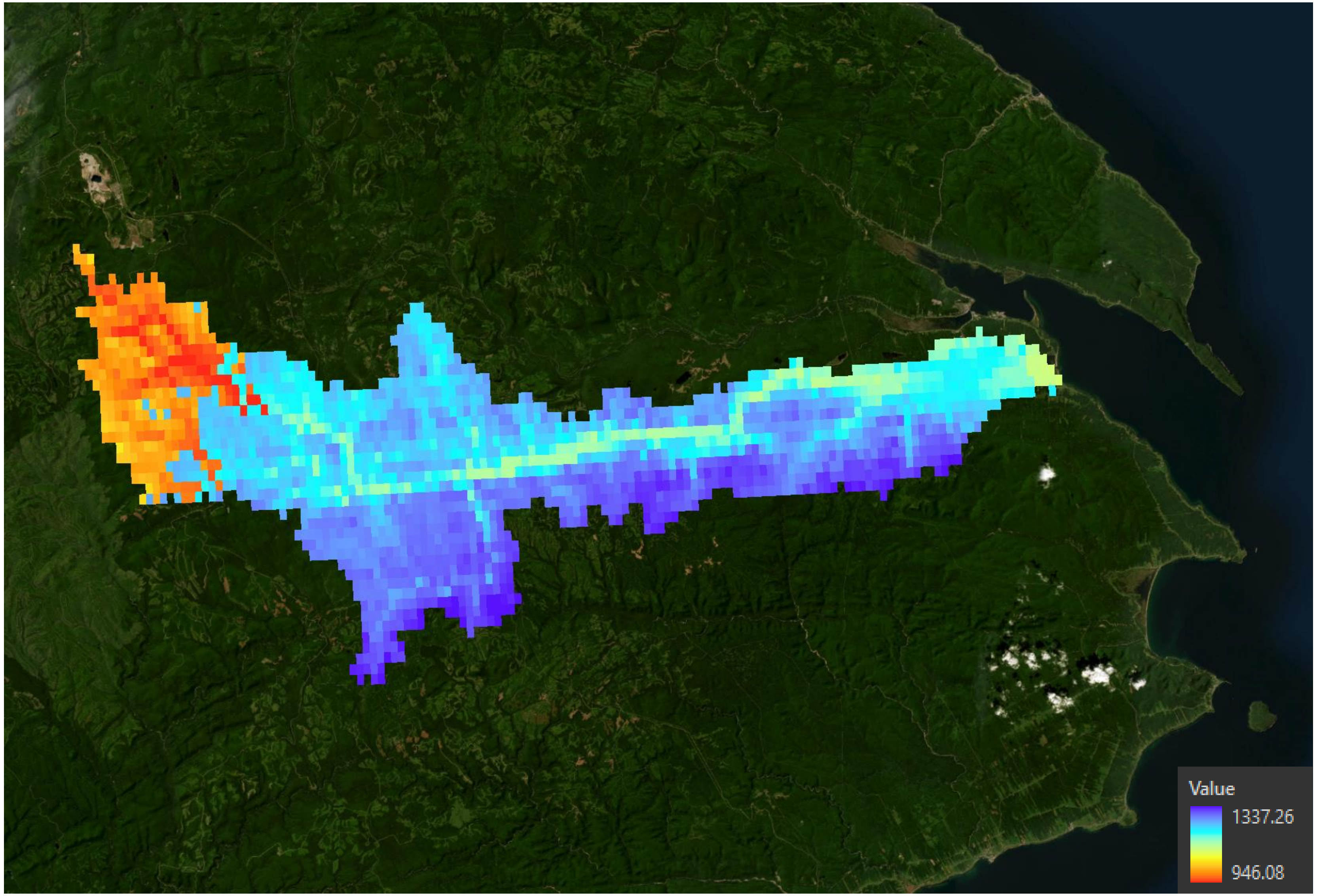
By summing the rainfall erosivity of all rainfall events, the annual rainfall erosivity index can be expressed as:

$$R_y = \sum_{j=1}^{Y} R_j$$

E_j is kinetic energy (MJ/mm)
E_i is unitary kinetic energy (MJ/mm*ha) that was extrapolated from the relationship between raindrop diameter and rainfall intensity (Laws & Parsons, 1943).

A= **R**KLSCP
R= Rainfall Erosivity Factor

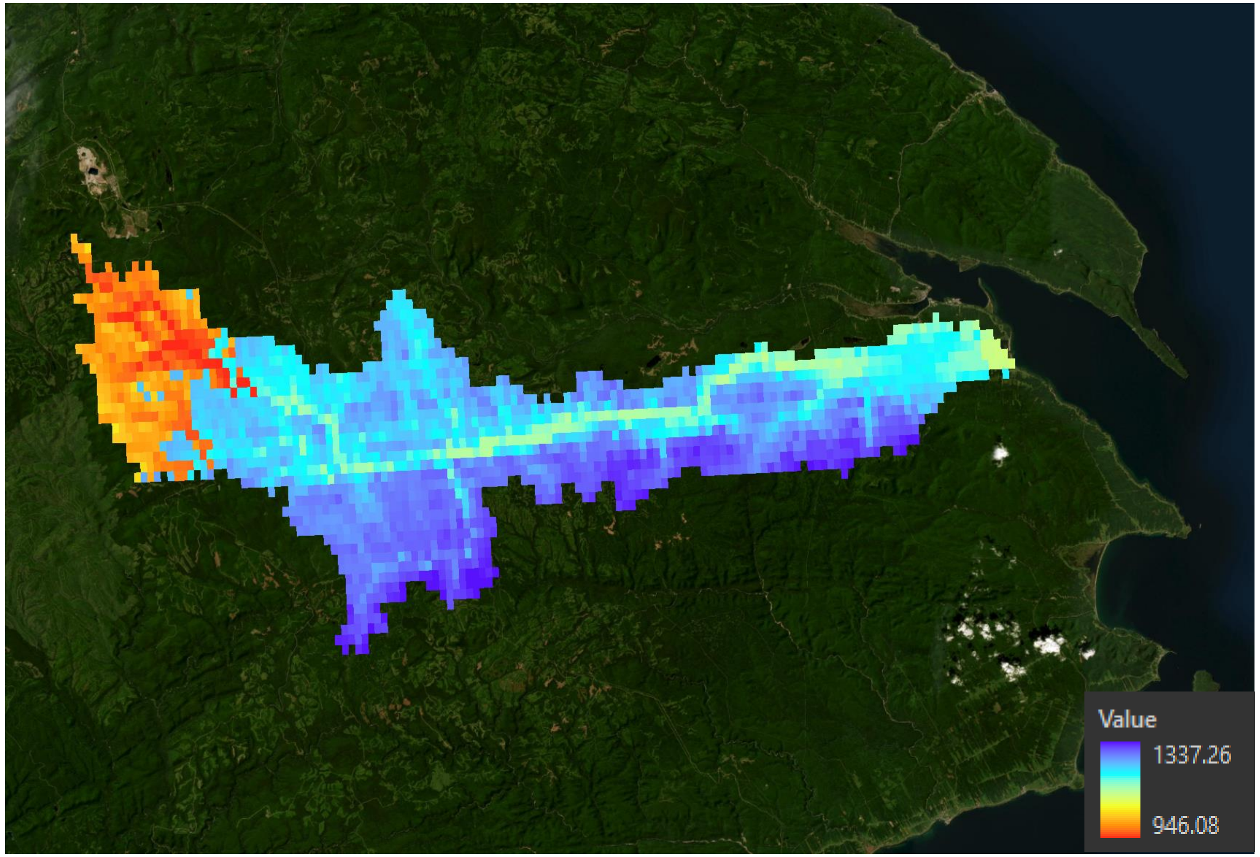
Rainfall Erosivity in the Gaspe Peninsula



Rain Erosivity (R) = 946 – 1337 MJ mm ha^{-1} h^{-1} yr^{-1}

A= **R**KLSCP
R= Rainfall Erosivity Factor

Rainfall Erosivity in the Gaspe Peninsula



Rain Erosivity (R) = 946 – 1337 MJ mm ha^{-1} h^{-1} yr^{-1}

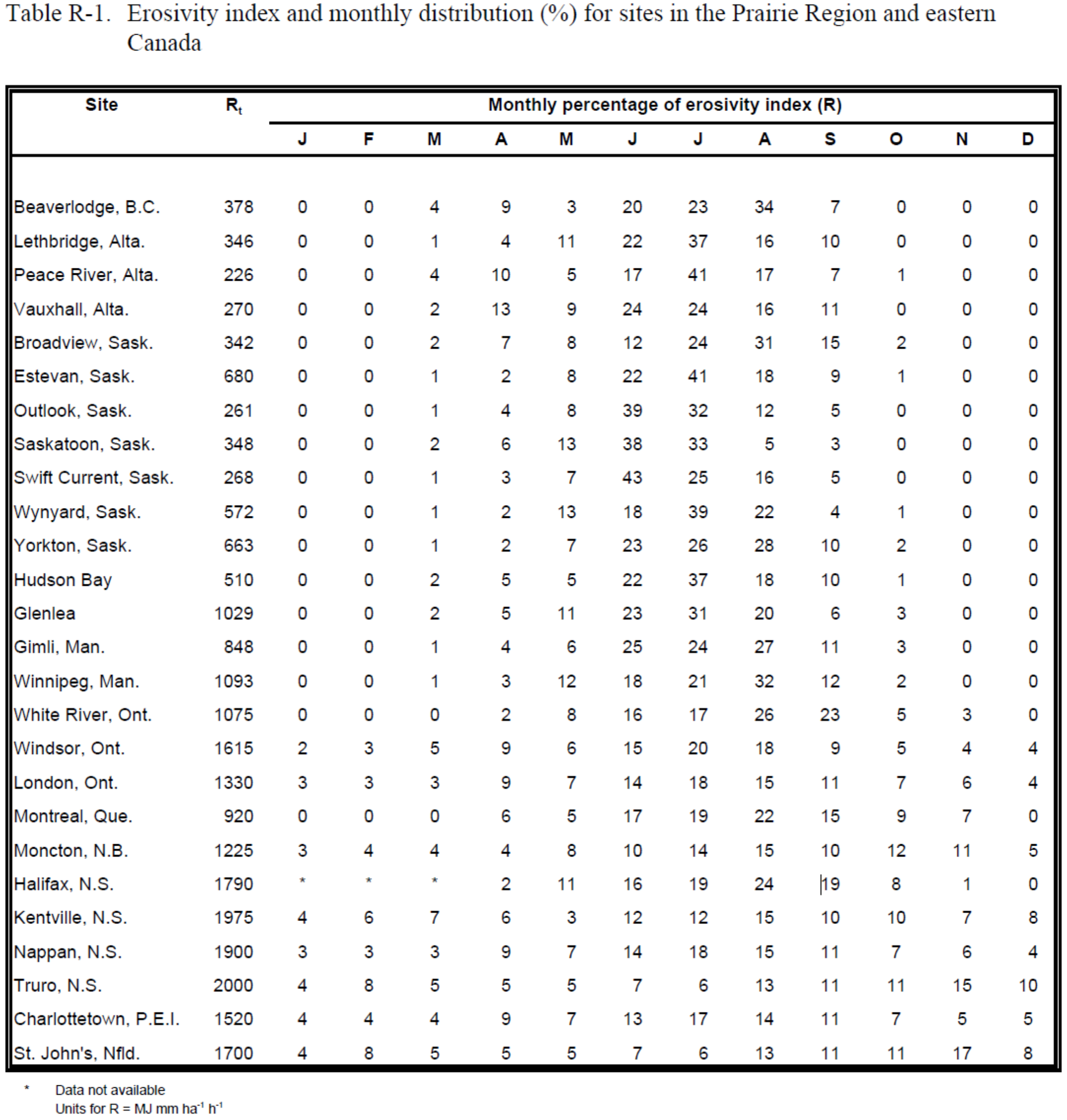


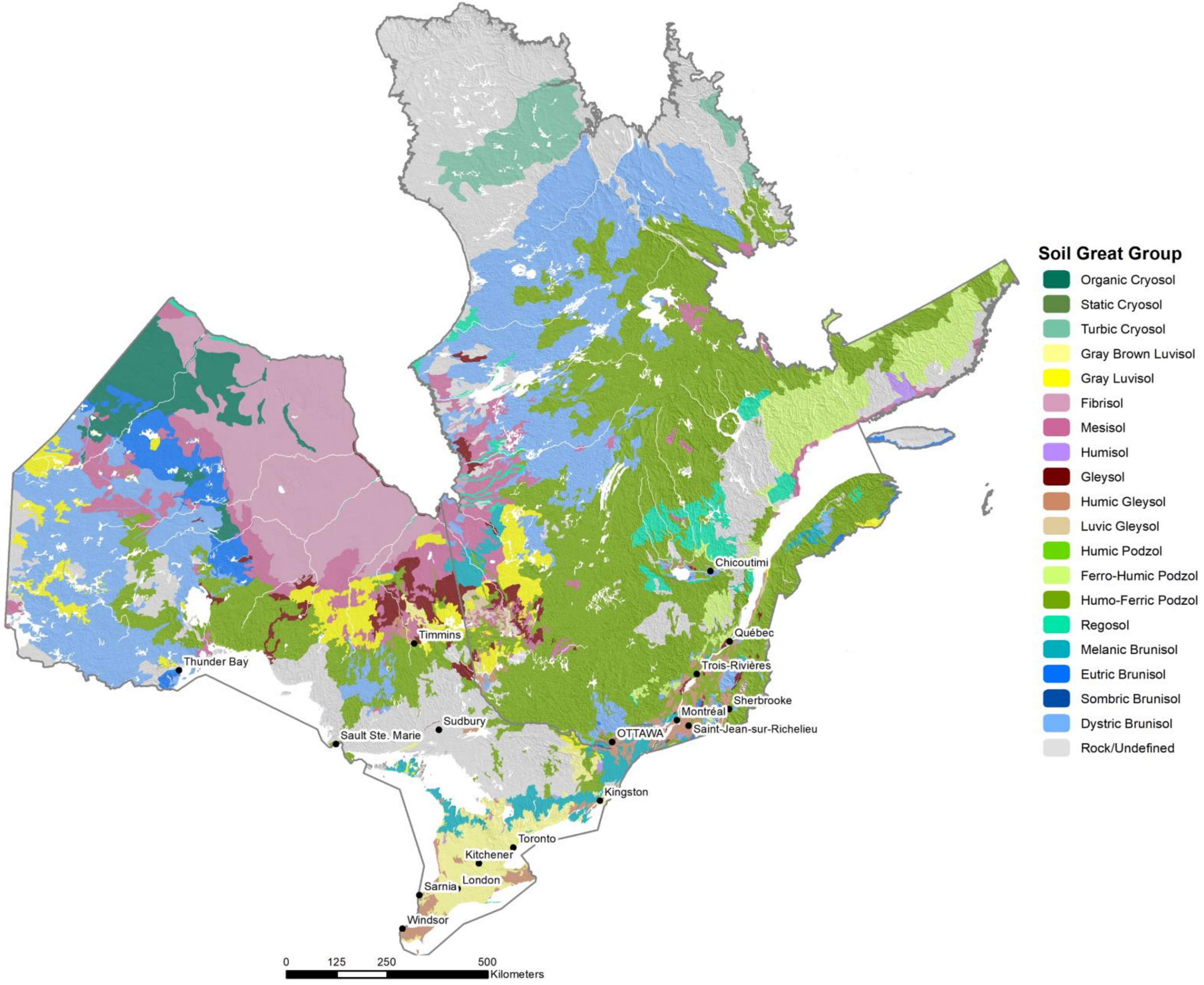
Table R-1. Erosivity index and monthly distribution (%) for sites in the Prairie Region and eastern Canada

Site	R_t	Monthly percentage of erosivity index (R)											
		J	F	M	A	M	J	J	A	S	O	N	D
Beaverlodge, B.C.	378	0	0	4	9	3	20	23	34	7	0	0	0
Lethbridge, Alta.	346	0	0	1	4	11	22	37	16	10	0	0	0
Peace River, Alta.	226	0	0	4	10	5	17	41	17	7	1	0	0
Vauxhall, Alta.	270	0	0	2	13	9	24	24	16	11	0	0	0
Broadview, Sask.	342	0	0	2	7	8	12	24	31	15	2	0	0
Estevan, Sask.	680	0	0	1	2	8	22	41	18	9	1	0	0
Outlook, Sask.	261	0	0	1	4	8	39	32	12	5	0	0	0
Saskatoon, Sask.	348	0	0	2	6	13	38	33	5	3	0	0	0
Swift Current, Sask.	268	0	0	1	3	7	43	25	16	5	0	0	0
Wynyard, Sask.	572	0	0	1	2	13	18	39	22	4	1	0	0
Yorkton, Sask.	663	0	0	1	2	7	23	26	28	10	2	0	0
Hudson Bay	510	0	0	2	5	5	22	37	18	10	1	0	0
Glenlea	1029	0	0	2	5	11	23	31	20	6	3	0	0
Gimli, Man.	848	0	0	1	4	6	25	24	27	11	3	0	0
Winnipeg, Man.	1093	0	0	1	3	12	18	21	32	12	2	0	0
White River, Ont.	1075	0	0	0	2	8	16	17	26	23	5	3	0
Windsor, Ont.	1615	2	3	5	9	6	15	20	18	9	5	4	4
London, Ont.	1330	3	3	3	9	7	14	18	15	11	7	6	4
Montreal, Que.	920	0	0	0	6	5	17	19	22	15	9	7	0
Moncton, N.B.	1225	3	4	4	4	8	10	14	15	10	12	11	5
Halifax, N.S.	1790	*	*	*	2	11	16	19	24	19	8	1	0
Kentville, N.S.	1975	4	6	7	6	3	12	12	15	10	10	7	8
Nappan, N.S.	1900	3	3	3	9	7	14	18	15	11	7	6	4
Truro, N.S.	2000	4	8	5	5	5	7	6	13	11	11	15	10
Charlottetown, P.E.I.	1520	4	4	4	9	7	13	17	14	11	7	5	5
St. John's, Nfld.	1700	4	8	5	5	5	7	6	13	11	11	17	8

* Data not available
Units for R = MJ mm ha^{-1} h^{-1}

A= R**K**LSCP
K= Soil Erodibility Factor

Soils of Canada



The predominant soil group in the Gaspe Peninsula is Humo-Ferric Podzol. Gray Luvisol and Sombric Brunisol are present in the Southern shore of the Gaspe Peninsula with a small central portion of Regosol.

A= R**K**LSCP
K= Soil Erodibility Factor

Soil Erodibility

The soil erodibility factor K is a quantitative measure of a soil's inherent susceptibility and resistance to erosion and the soil's influence on runoff amount and rate.

In the absence of field tests, these values can be estimated using relationships based on physical and chemical soil properties.

Fischer, G., F. Nachtergaele, S. Prieler, H.T. van Velthuizen, L. Verelst, D. Wiberg, 2008. *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. IIASA, Laxenburg, Austria and FAO, Rome, Italy.

A= R**K**LSCP
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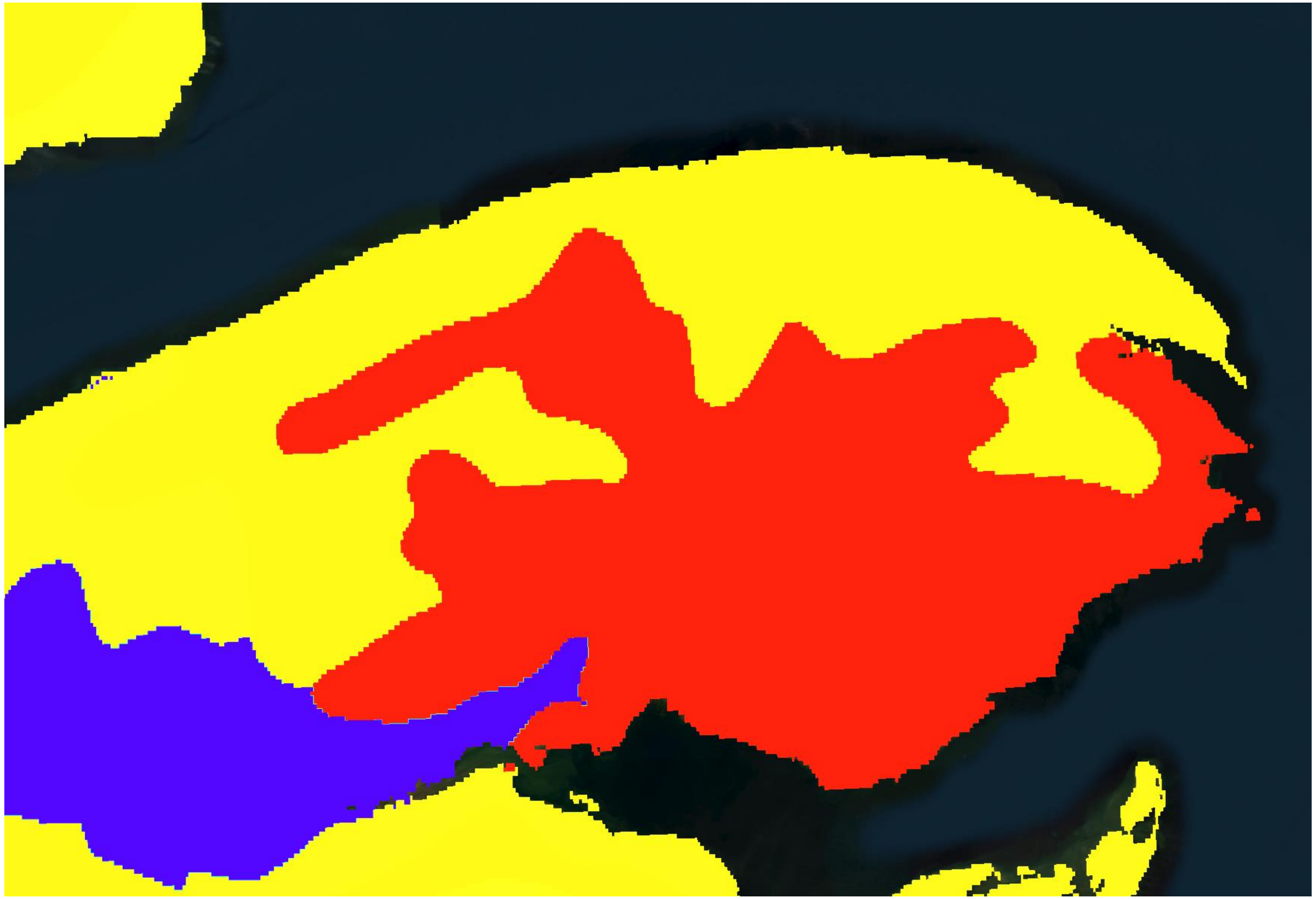
Soil Erodibility



Resolution: 1 km
Measurement Unit: tons per ha

Fischer, G., F. Nachtergaele, S. Prieler, H.T. van Velthuizen, L. Verelst, D. Wiberg, 2008. *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. IIASA, Laxenburg, Austria and FAO, Rome, Italy.

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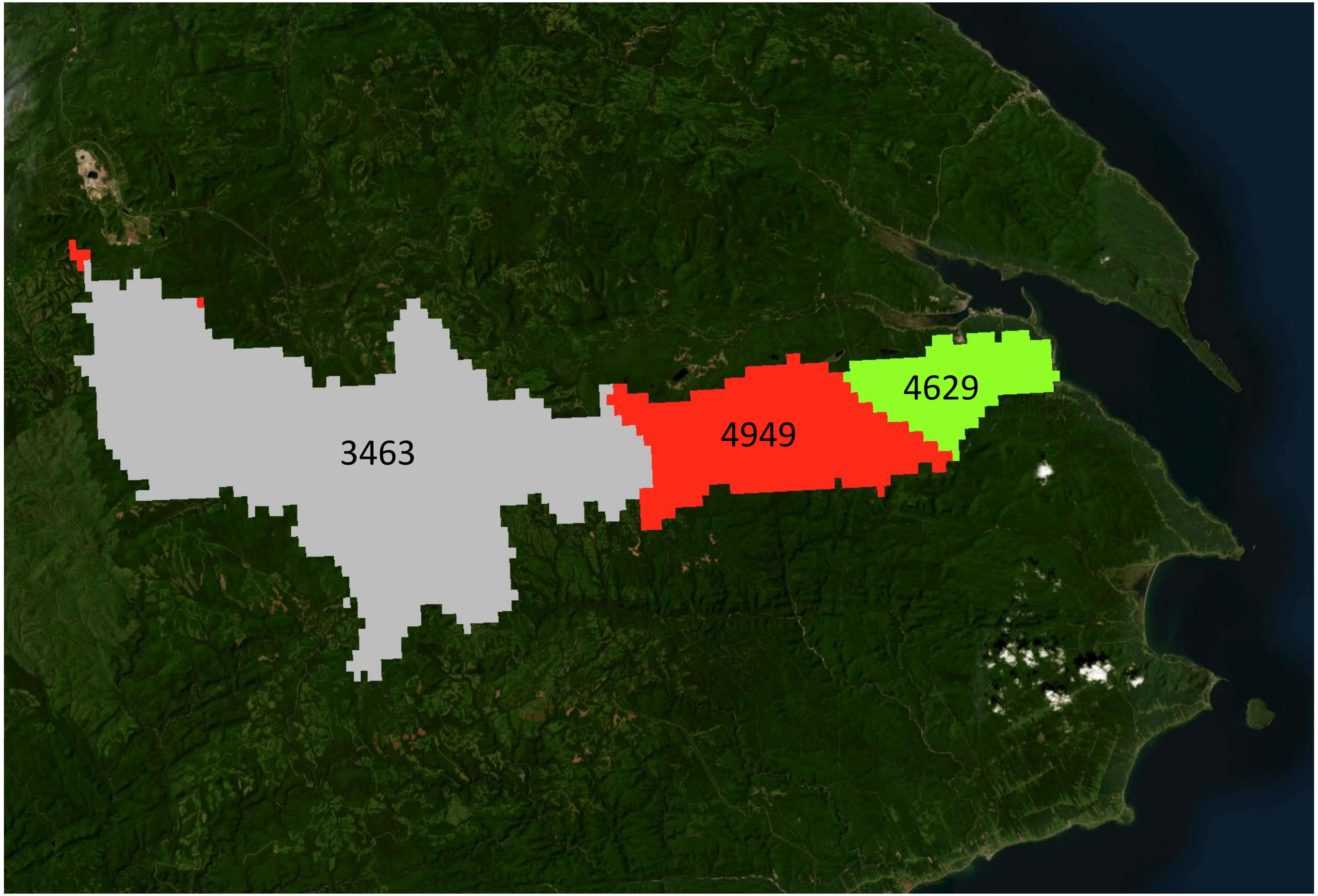
K= Soil Erodibility Factor

Soil Erodibility

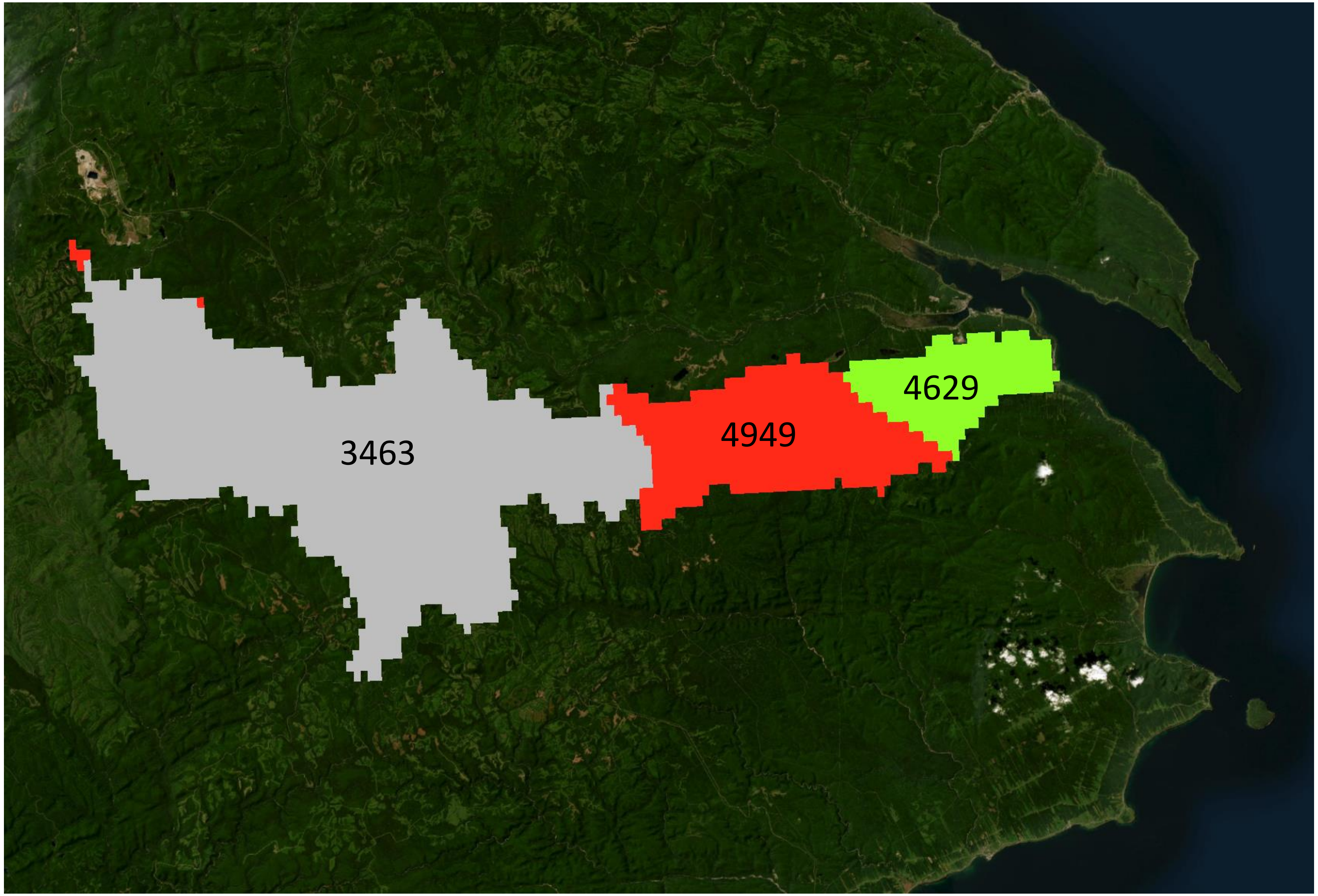


Variables Extracted:

- Sand (%)
- Silt (%)
- Clay (%)
- Organic Matter (%)

A= R**K**LSCP
K= Soil Erodibility Factor

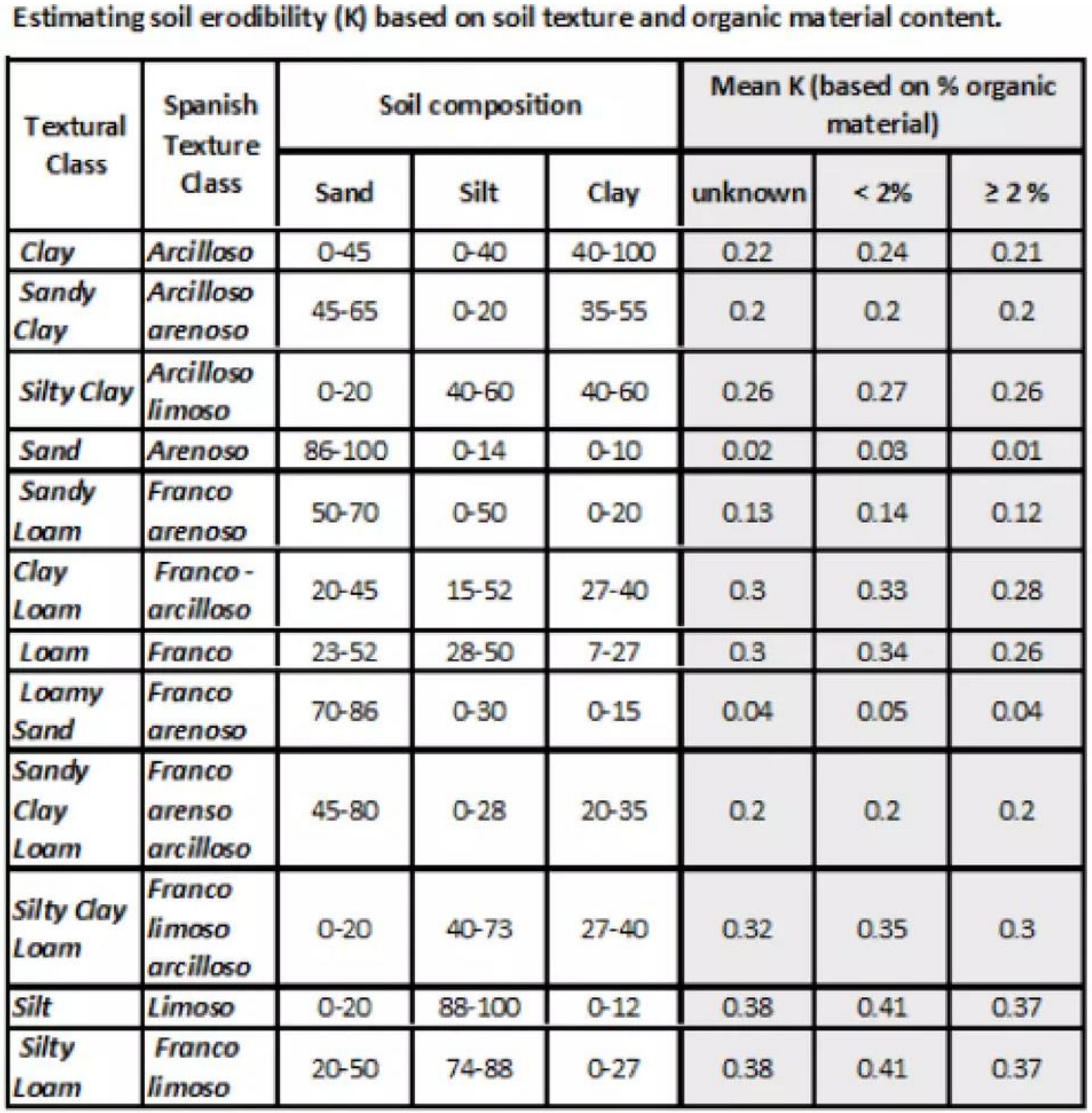
Soil Erodibility



Each raster value is used as a reference code to the included Microsoft Access table for soil information.

A= R**K**LSCP
K= Soil Erodibility Factor

Soil Erodibility



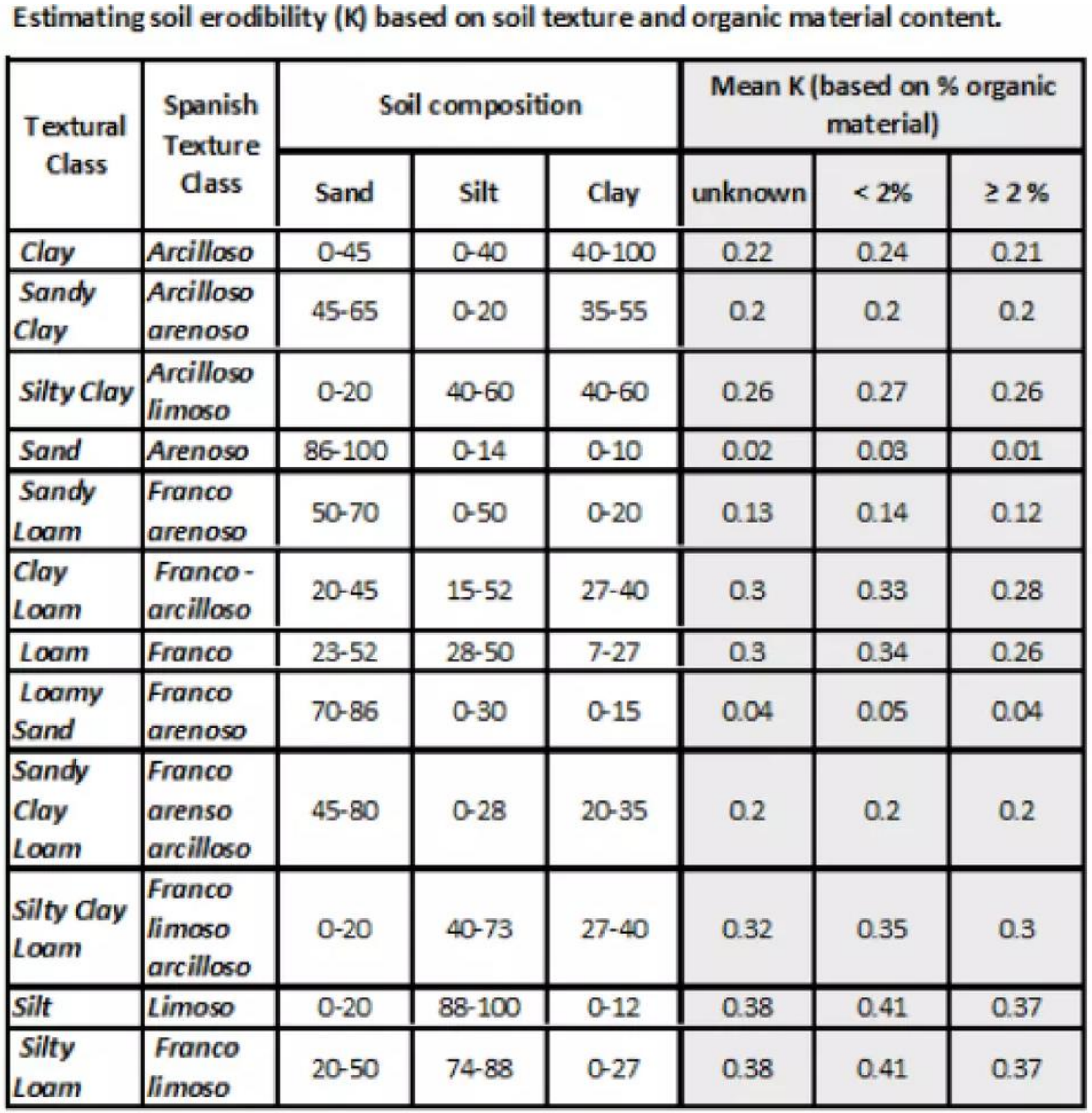
Estimating soil erodibility (K) based on soil texture and organic material content.

Textural Class	Spanish Texture Class	Soil composition			Mean K (based on % organic material)		
		Sand	Silt	Clay	unknown	< 2%	≥ 2 %
Clay	*Arcilloso*	0-45	0-40	40-100	0.22	0.24	0.21
Sandy Clay	*Arcilloso arenoso*	45-65	0-20	35-55	0.2	0.2	0.2
Silty Clay	*Arcilloso limoso*	0-20	40-60	40-60	0.26	0.27	0.26
Sand	*Arenoso*	86-100	0-14	0-10	0.02	0.03	0.01
Sandy Loam	*Franco arenoso*	50-70	0-50	0-20	0.13	0.14	0.12
Clay Loam	*Franco - arcilloso*	20-45	15-52	27-40	0.3	0.33	0.28
Loam	*Franco*	23-52	28-50	7-27	0.3	0.34	0.26
Loamy Sand	*Franco arenoso*	70-86	0-30	0-15	0.04	0.05	0.04
Sandy Clay Loam	*Franco arenso arcilloso*	45-80	0-28	20-35	0.2	0.2	0.2
Silty Clay Loam	*Franco limoso arcilloso*	0-20	40-73	27-40	0.32	0.35	0.3
Silt	*Limoso*	0-20	88-100	0-12	0.38	0.41	0.37
Silty Loam	*Franco limoso*	20-50	74-88	0-27	0.38	0.41	0.37

Soil ID	Sand (%)	Silt (%)	Clay (%)	Organic Carbon (%)
3463	58	37	5	2.221
4629	43	46	11	4.708
4949	54	40	6	7.217

A= R**K**LSCP
K= Soil Erodibility Factor

Soil Erodibility



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Sandy Clay	*Arcilloso arenoso*	45-65	0-20	35-55	0.2	0.2	0.2
Silty Clay	*Arcilloso limoso*	0-20	40-60	40-60	0.26	0.27	0.26
Sand	*Arenoso*	86-100	0-14	0-10	0.02	0.03	0.01
Sandy Loam	*Franco arenoso*	50-70	0-50	0-20	0.13	0.14	0.12
Clay Loam	*Franco - arcilloso*	20-45	15-52	27-40	0.3	0.33	0.28
Loam	*Franco*	23-52	28-50	7-27	0.3	0.34	0.26
Loamy Sand	*Franco arenoso*	70-86	0-30	0-15	0.04	0.05	0.04
Sandy Clay Loam	*Franco arenso arcilloso*	45-80	0-28	20-35	0.2	0.2	0.2
Silty Clay Loam	*Franco limoso arcilloso*	0-20	40-73	27-40	0.32	0.35	0.3
Silt	*Limoso*	0-20	88-100	0-12	0.38	0.41	0.37
Silty Loam	*Franco limoso*	20-50	74-88	0-27	0.38	0.41	0.37

We need organic matter for our soul erodibility (K) value.

Organic Carbon can be converted to organic matter by:

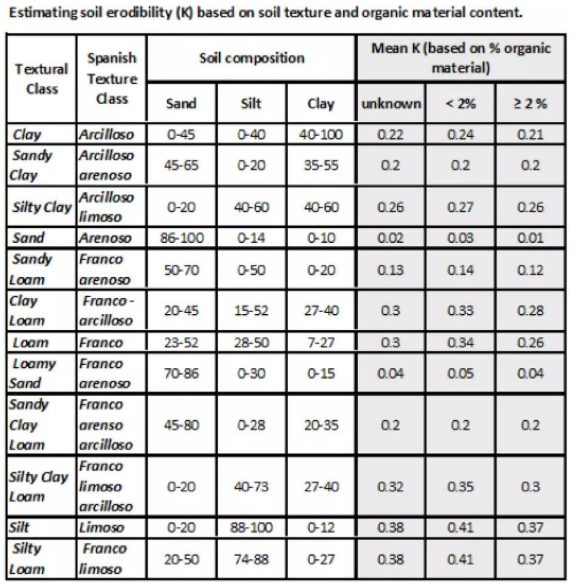
Organic Matter= 1.72*Organic Carbon

(IPCC-AFP:U Report 2006)

Soil ID	SAND	SILT	CLAY	Organic Carbon	Organic Matter	Textural Class	Soil Erodibility (K)
3463	58	37	5	2.221	3.82012	Sandy Loam	0.12
4629	43	46	11	4.708	8.09776	Loam	0.26
4949	54	40	6	7.217	12.41324	Sandy Loam	0.12

Soil Erodibility

A= R**K**LSCP
K= Soil Erodibility Factor



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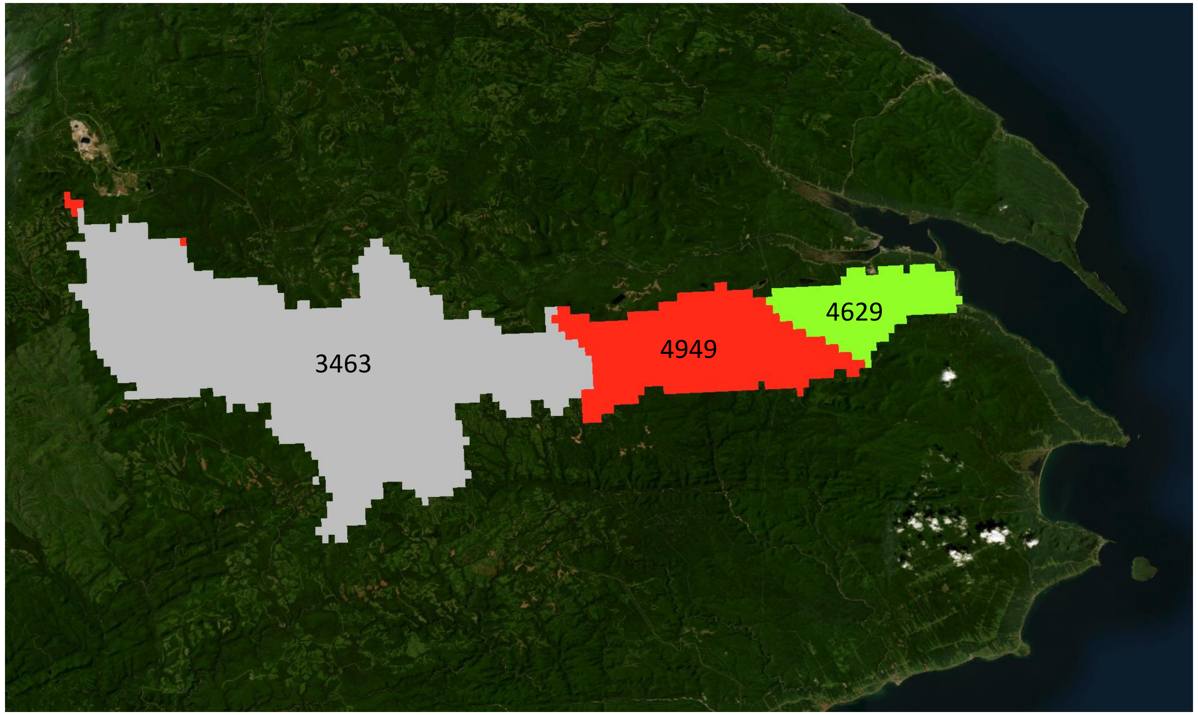
Silty Clay	*Arcilloso limoso*	0-20	40-60	40-60	0.26	0.27	0.26
Sand	*Arenoso*	86-100	0-14	0-10	0.02	0.03	0.01
Sandy Loam	*Franco arenoso*	50-70	0-50	0-20	0.13	0.14	0.12
Clay Loam	*Franco - arcilloso*	20-45	15-52	27-40	0.3	0.33	0.28
Loam	*Franco*	23-52	28-50	7-27	0.3	0.34	0.26
Loamy Sand	*Franco arenoso*	70-86	0-30	0-15	0.04	0.05	0.04
Sandy Clay Loam	*Franco arenso arcilloso*	45-80	0-28	20-35	0.2	0.2	0.2
Silty Clay Loam	*Franco limoso arcilloso*	0-20	40-73	27-40	0.32	0.35	0.3
Silt	*Limoso*	0-20	88-100	0-12	0.38	0.41	0.37
Silty Loam	*Franco limoso*	20-50	74-88	0-27	0.38	0.41	0.37



Soil ID	Textural Class	Soil Erodibility (K)
3463	Sandy Loam	0.12
4629	Loam	0.26
4949	Sandy Loam	0.12

A= RK**LS**CP
L,S= Length and steepness of slope factor

Length and steepness of slope factor

- Accounts for the effects of slope angle and length on erosion
- Adjusts the erosion prediction for a given slope length and slope angle to account for differences from conditions present at standard erosion monitoring plots on which the USLE was based (72 ft or 22 m long, 9% slopes; Wischmeier and Smith, 1978)
- As slope length increases (L), erosion increases, due to the accumulated runoff direction of a downward slope.
- As slope steepness (S) increases, erosion potential increases, due to increased velocity of runoff.

A= RK**LS**CP

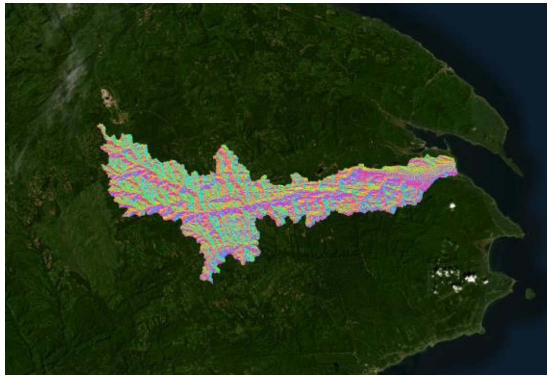
L,S= L,S= Length and steepness of slope factor

Length and steepness of slope factor

$$LS = \left(flow\ accumulation \times \frac{Cell\ Size}{22.13}\right)^{0.5} \times \frac{Sin\ (Slope)^{1.3}}{0.0896}$$

Fill DEM

Flow Direction



Flow Accumulation

$$\left(flow\ accumulation \times \frac{Cell\ Size}{22.13}\right)^{0.5}$$

Percent Rise Slope

$$\frac{Sin\ (Slope)^{1.3}}{0.0896}$$

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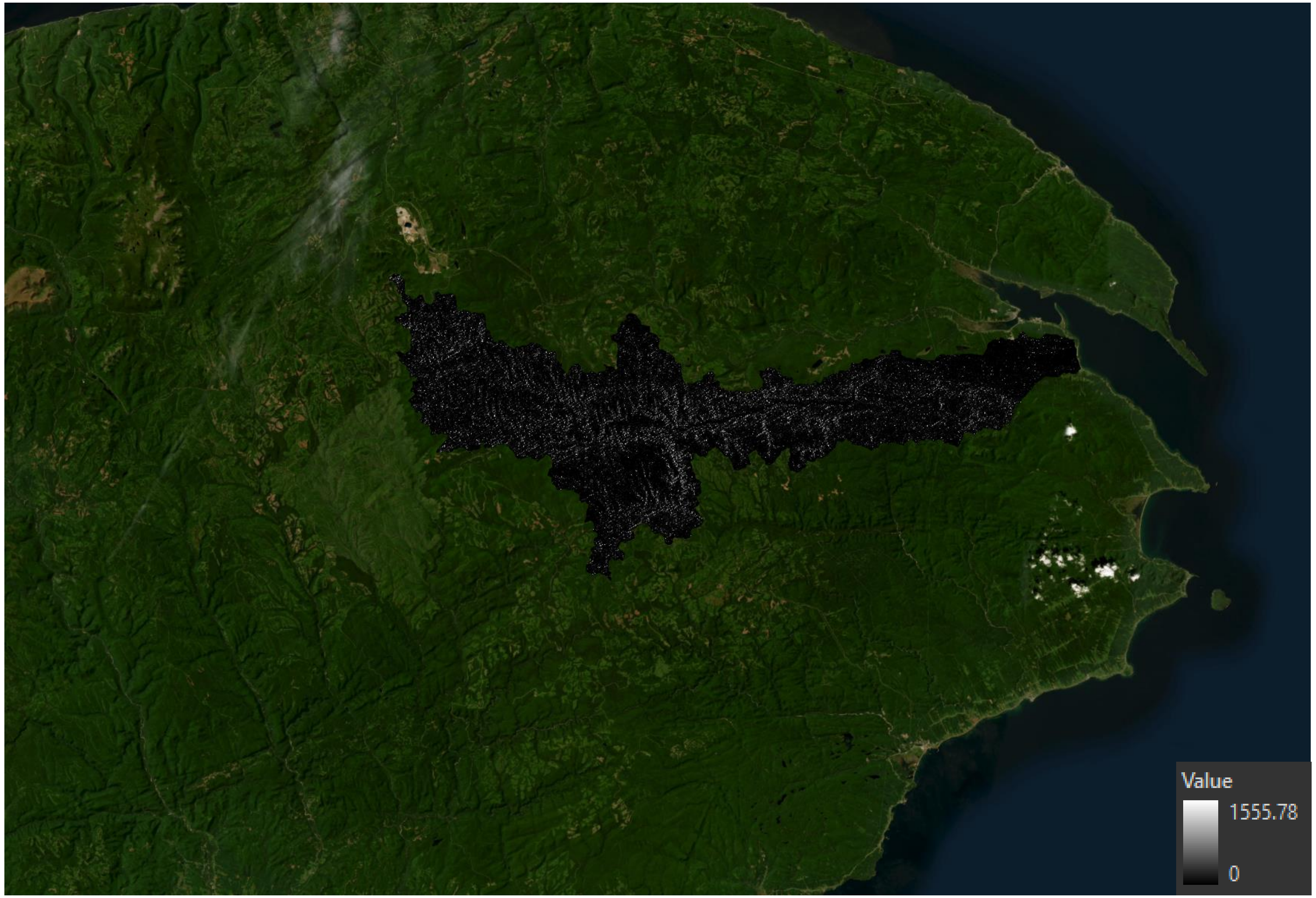
L,S= L,S= Length and steepness of slope factor

Length and steepness of slope factor

$$LS = \left(flow\ accumulation \times \frac{Cell\ Size}{22.13}\right)^{0.5} \times \frac{Sin\ (Slope)}{0.0896}^{1.3}$$

LS Raster



A= RKLS**C**P
C= Crop Management Factor

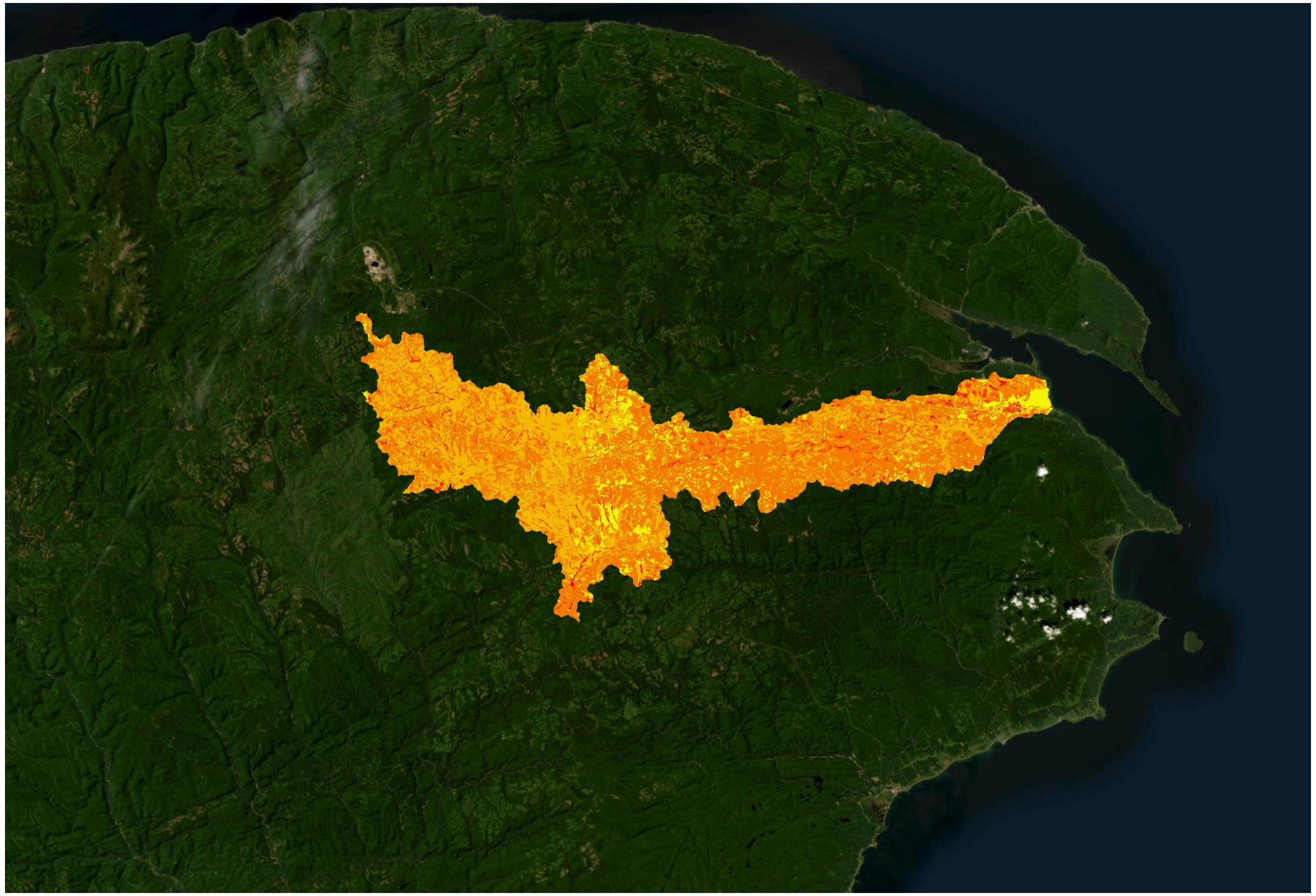
Land Use Index

Source: DonnesQuebec

LULC Class Number	Class Name	C Value
1	Water	0
2	Forest	0.025
3	Grass	0.02
4	Flooded Vegetation	1
5	Crops	0.05
6	Shurbs	0.4
7	Developed Area	1
8	Bare Ground	1

A= RKLS**C**P
C= Crop Management Factor

Land Use Index



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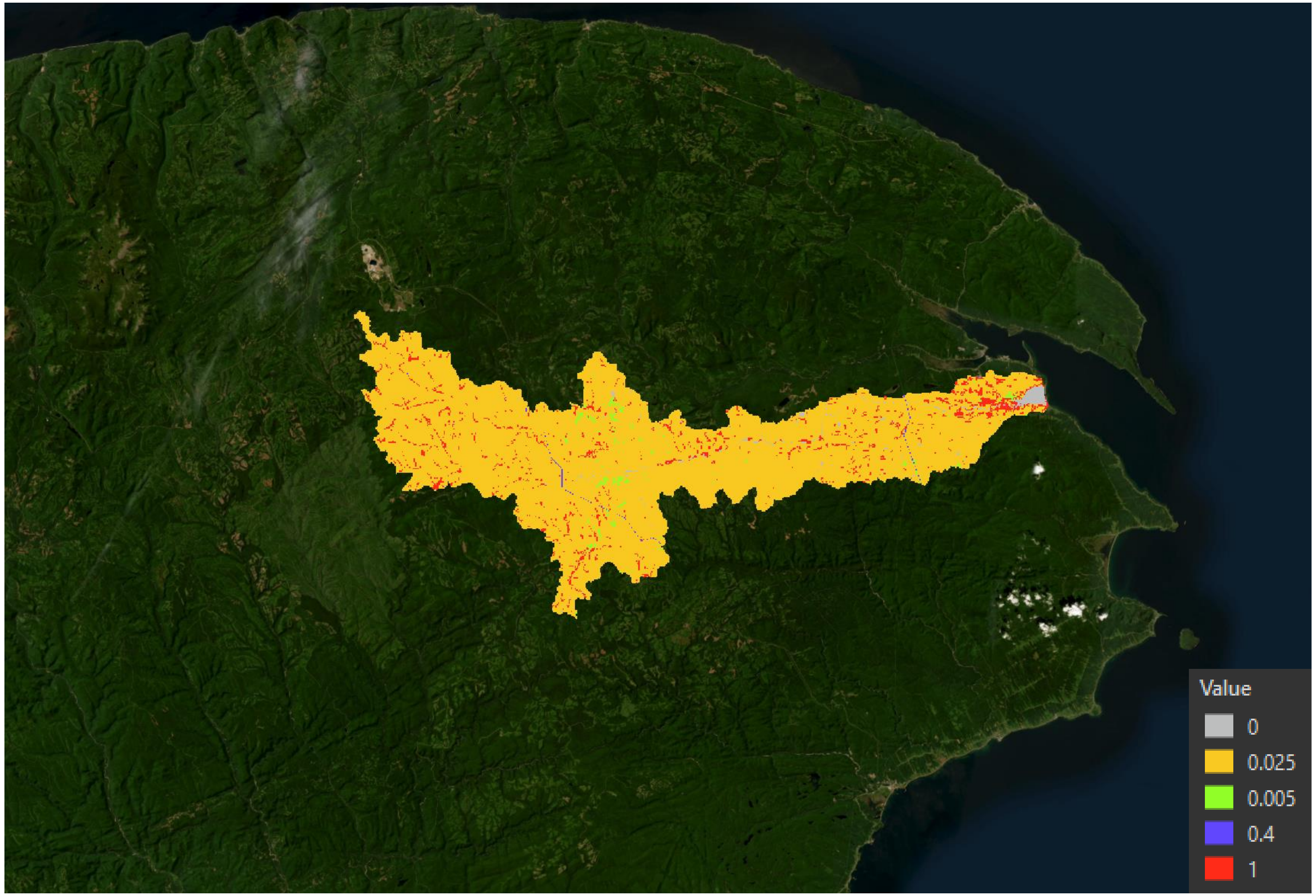
Land Use Index



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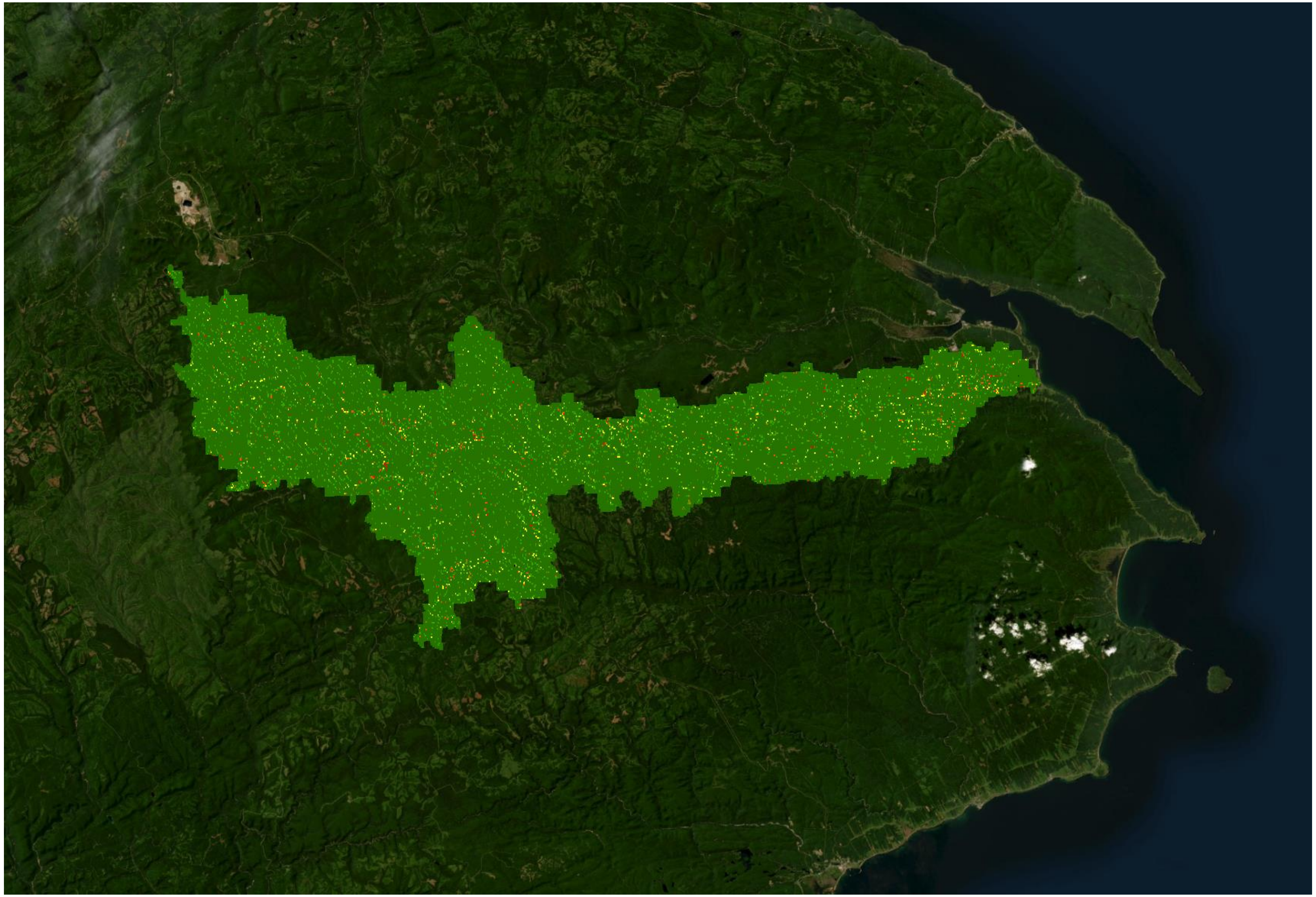
The Universal Soil Loss Equation (USLE)
$A= RKLSCP$



A= mean annual soil loss

R= Rainfall Erosivity Factor

K= Soil Erodibility Factor

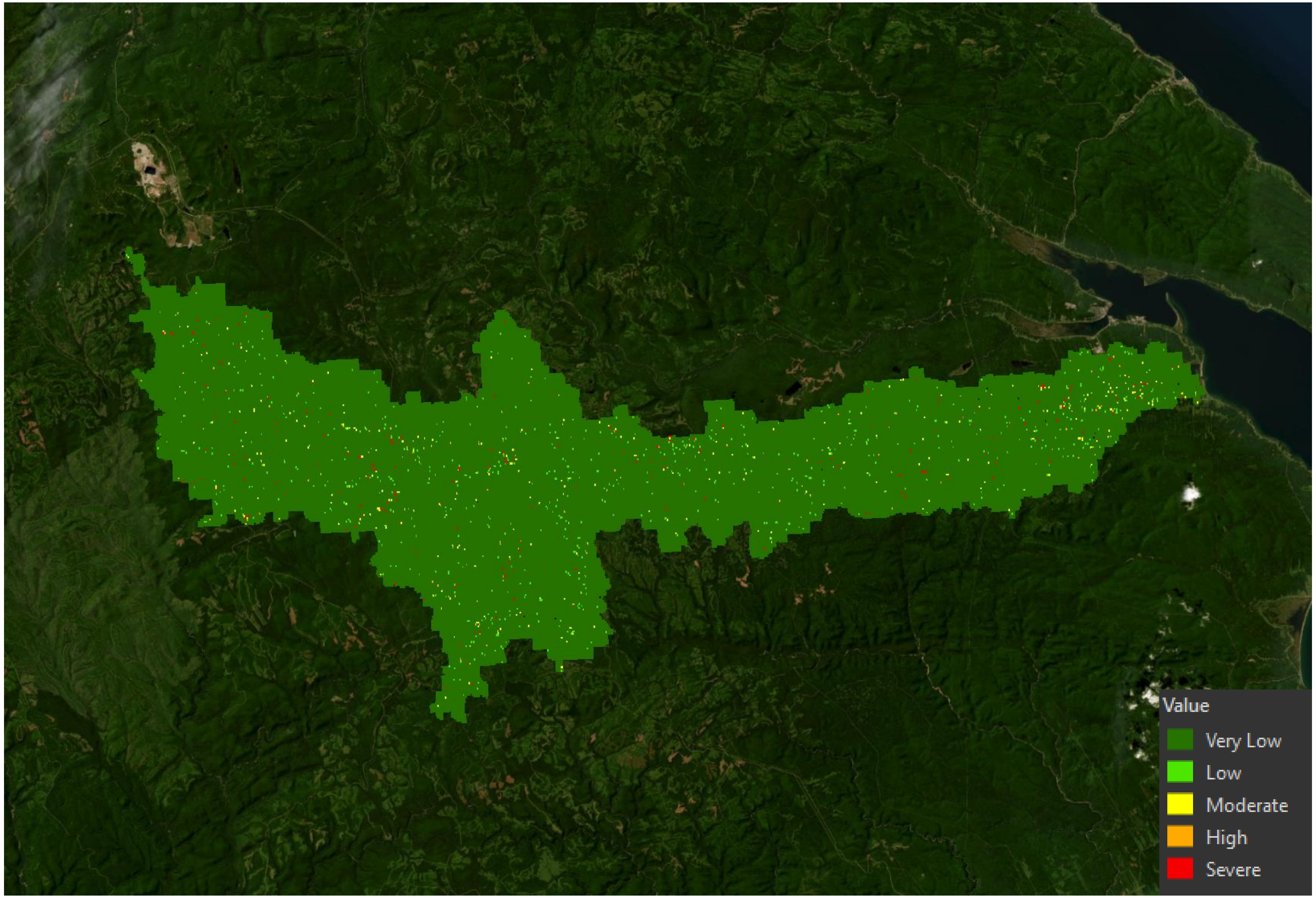
L= Slope Length Factor

S= Slope Steepness Factor

C= Crop Management Factor

P= Erosion Control Practice Factor

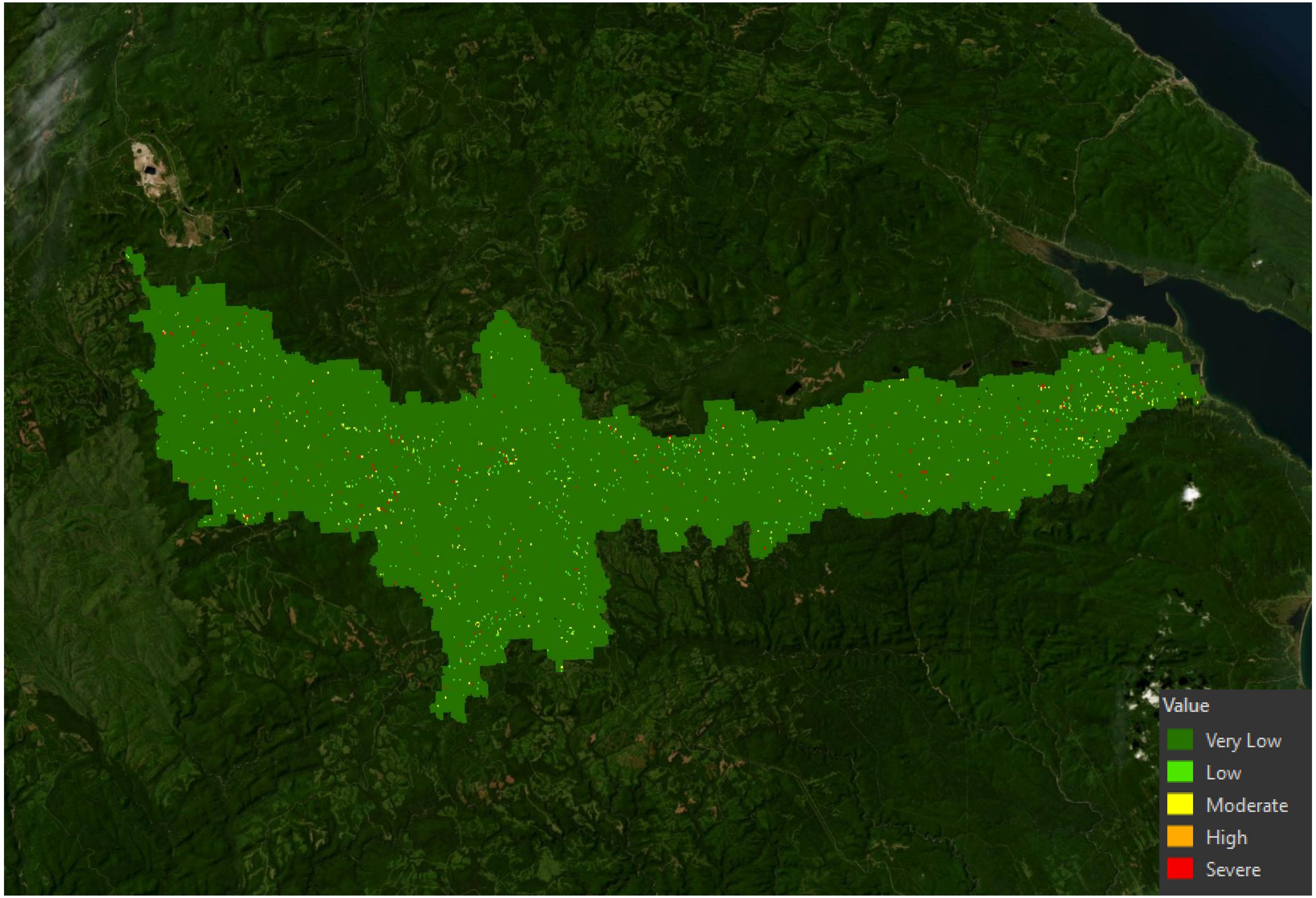
The Universal Soil Loss Equation (USLE)
A= RKLSCP



Soil Erosion Class	Potential Soil Loss	
	tonnes/hectare/year	tons/acre/year
Very Low	< 6	< 3
Low	6-11	3-5
Moderate	11-22	5-10
High	22-33	10-15
Severe	> 33	> 15

The Universal Soil Loss Equation (USLE)

A= RKLSCP



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The Universal Soil Loss Equation (USLE)
A= RKLSCP

The USLE identified 69,623 sites that exceeded 6 tonnes/hectare/year.

The USLE identified 1,332 sites that exceeded 6 tonnes/hectare/year.

There are 645 sites that are Moderate annual soil loss or higher. Of the 645 sites, 395 sites were within 100 meters of a stream.

Only 3 sites were within 50 meters of a culvert (Doesn’t mean upstream sedimentation does not impact culvert)

Soil Erosion Class	Potential Soil Loss	
	tonnes/hectare/year	tons/acre/year
Very Low	< 6	< 3
Low	6-11	3-5
Moderate	11-22	5-10
High	22-33	10-15
Severe	> 33	> 15

Soil Erosion Class	Number of sites
Very Low	68291
Low	687
Moderate	370
High	57
Severe	218