



Image from: <https://www.fs.fed.us/science-technology/geology/groundwater/learnmore>

Representing uncertainty in groundwater vulnerability assessments

A case study AVI assessment of NTS Map Area 073B (Saskatoon)

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Overview

Groundwater vulnerability assessments – definitions

Uncertainty – sources and relevance

Case study: NTS Map Area 073B (Saskatoon)

- Statistical characterization of hydraulic conductivity in Sask. Tills
- Uncertainty in Aquifer Vulnerability Index (AVI)

Groundwater Vulnerability and Policy

Groundwater contamination:

Cost of Prevention << Cost of Investigation, remediation, monitoring

Local scale – Site investigations, modelling

Regional scale – Groundwater vulnerability assessments (GVAs)

Groundwater Vulnerability Assessments:

- Groundwater management and planning
- Policy development
- General education and communication

Groundwater Vulnerability Assessments (GVAs)

Definitions

Specific vulnerability

- Hydrogeologic properties + contaminant & human behaviour

Intrinsic vulnerability

- Hydrogeologic properties

Resource vulnerability

- Single pathway

Source vulnerability

- Two pathways

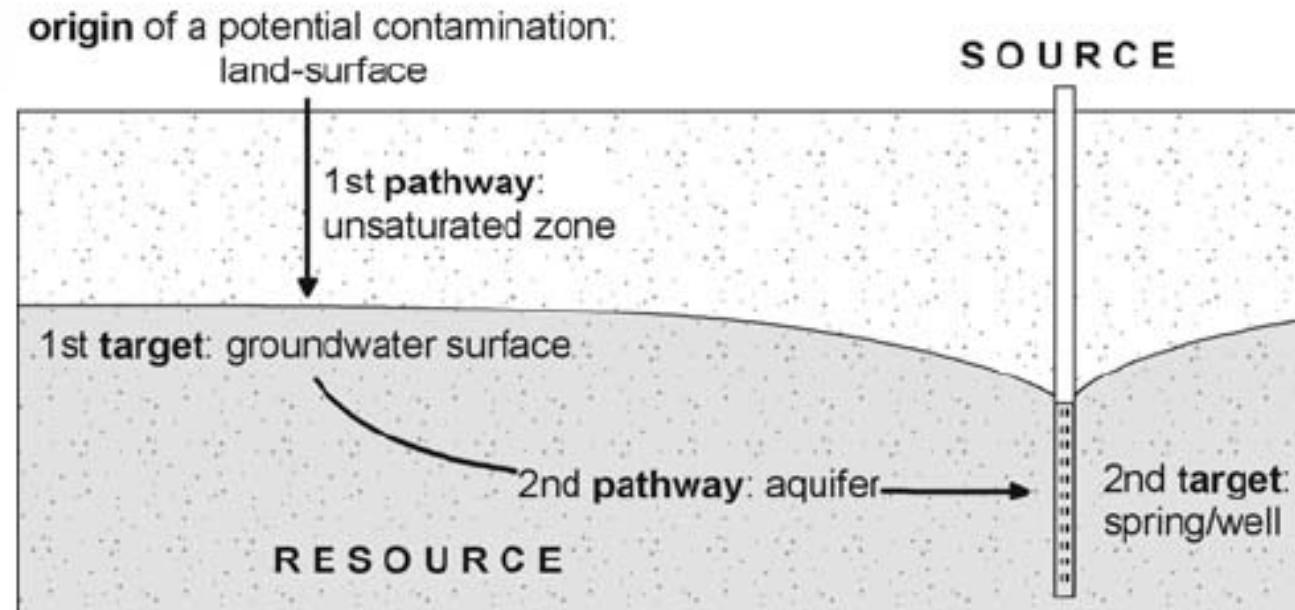


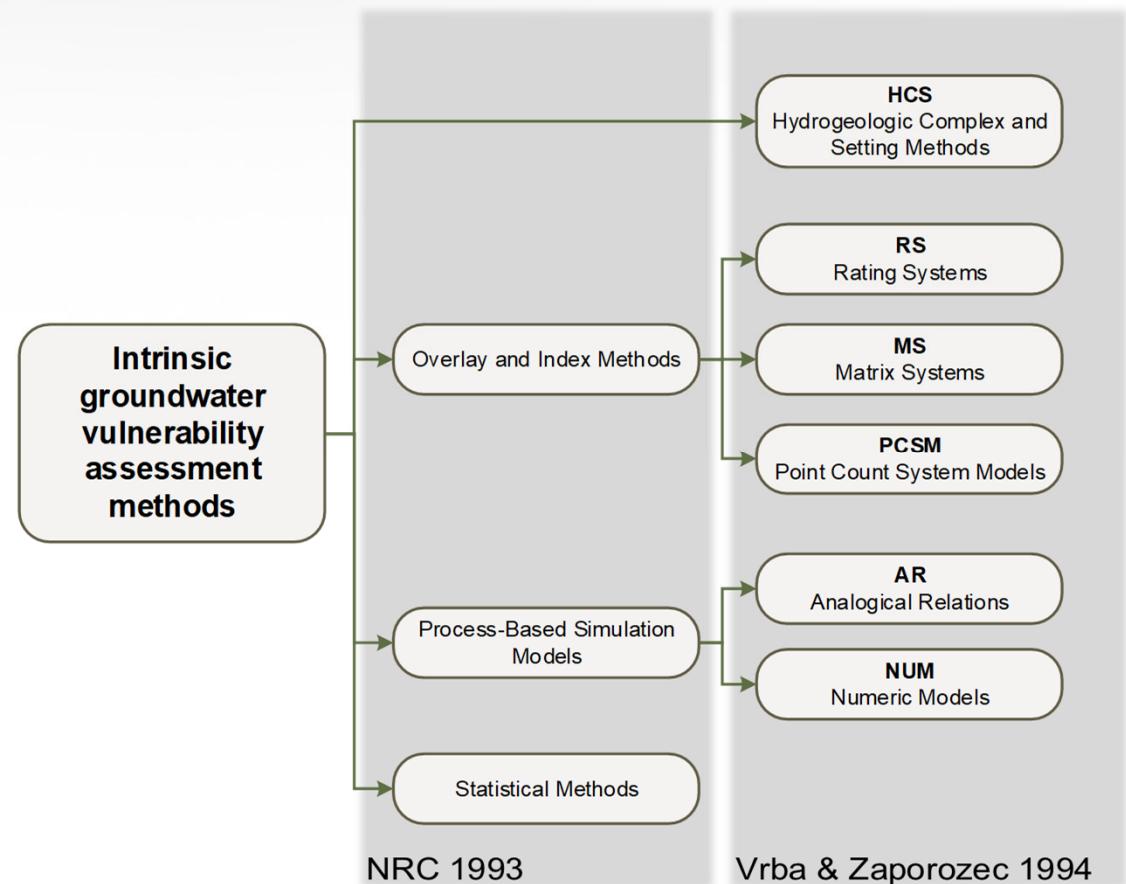
Image from: https://www.researchgate.net/figure/Illustration-of-the-origin-pathway-target-model-for-groundwater-vulnerability-mapping-and_fig2_22589887

Groundwater Vulnerability Assessments (GVAs)

Categorization of Intrinsic GVAs

Three elements of GVAs

1. Input parameters
2. Rating and weighting system
3. Method of aggregation



Groundwater Vulnerability Assessments (GVAs)

Categorization of Intrinsic GVAs

Variety of methods:

- Hydro. conditions
- Processes

Common product:

- Deterministic
- Vulnerability map(s)

Shortcoming:

- Uncertainty

Groundwater vulnerability assessment method	Source/citation	Year	Type of assessment method	Qualitative rating															
				Consideration of multiple overlying units	Hydraulic conductivity of overlying units	Depth to water, depth of overlying units (Net Recharge)	Aquifer media, lithology	Soil (topsoil)	Topography (percent slope)	Vadose zone effect	Hydraulic conductivity of aquifer	Precipitation	Fracturing, karst, preferential flow paths	Proximity of catchment, recharge zones	Subsoil, surficial geology, lithology of overlying unit(s)	Hydraulic head loss between surface and aquifer	Temporal distribution of rainfall	Porosity of overlying unit(s)	Land use, plant cover
DRASTIC	Aller et al.	1987	PCSM & HCS	Y				Y	Y	Y	Y	Y	Y	Y					
				(D)ept, (R)echarge, (A)quifer media, (S)oil, (T)opography, (I)mport of vadose zone, hydraulic (C)onductivity															
SINTACS	Civita	1994	PCSM	Y	Y			Y	Y	Y	Y	Y	Y	Y					
				Depth, infiltration, unsaturated and soil attenuation capacity, saturated zone, hydraulic conductivity, slope															
AVI	Van Stempvoort et al.	1993	AR		Y	Y	Y	Y											
				(A)quifer (V)ulnerability (I)ndex															
ISI	Ontario MOE	2001	AR /RS		Y	Y	Y												
				(I)ntrinsic (S)usceptibility (I)ndex															
DAT	Ross et al.	2004	NUM			Y	Y	Y									Y	Y	
				(D)ownward (A)dvection (T)ime of travel															
RTt	Oke et al.	2016	RS /AR			Y	Y				Y			Y					Y
				(R)echarge and (T)ravel (t)ime															
GOD	Foster et al.	1987	RS	Y				Y								Y			Y
				(G)roundwater confinement, (O)verlying strata, (D)ept to groundwater															
EPIK	Doerfliger et al.	1999	PCMS	Y				Y			Y	Y				Y	Y	Y	
				(E)pikarst, (P)rotective cover, (I)nfiltration conditions, (K)arst network development															Y
PI	Goldscheider et al.	2000	RS /MS	Y	Y	Y	Y	Y	Y			Y			Y	Y	Y		Y Y
				(P)rotective cover, (I)nfiltration conditions															
COP	Vias et al.	2006	RS /MS	Y	Y			Y			Y	Y			Y	Y	Y	Y	Y Y
				(C)oncentration of flow, properties of (O)verlying Layers, (P)recipitation															

Uncertainty

Epistemic uncertainty – how certain are we that we know what we know?

Linguistic uncertainty – how vulnerable is vulnerable?

Uncertainty in GWVAs

Epistemic uncertainty – how certain are we that we know what we know?

- Input parameters
- Parameterization
- Model uncertainty

Linguistic uncertainty – how vulnerable is vulnerable?

- Index values
- Subjective interpretation

Uncertainty in GVAs

Epistemic uncertainty – how certain are we that we know what we know?

- **Input parameters – Natural variation**
- Parameterization
- Model uncertainty

Linguistic uncertainty – how vulnerable is vulnerable?

- Index values
- Subjective interpretation

Uncertainty in GWVAs

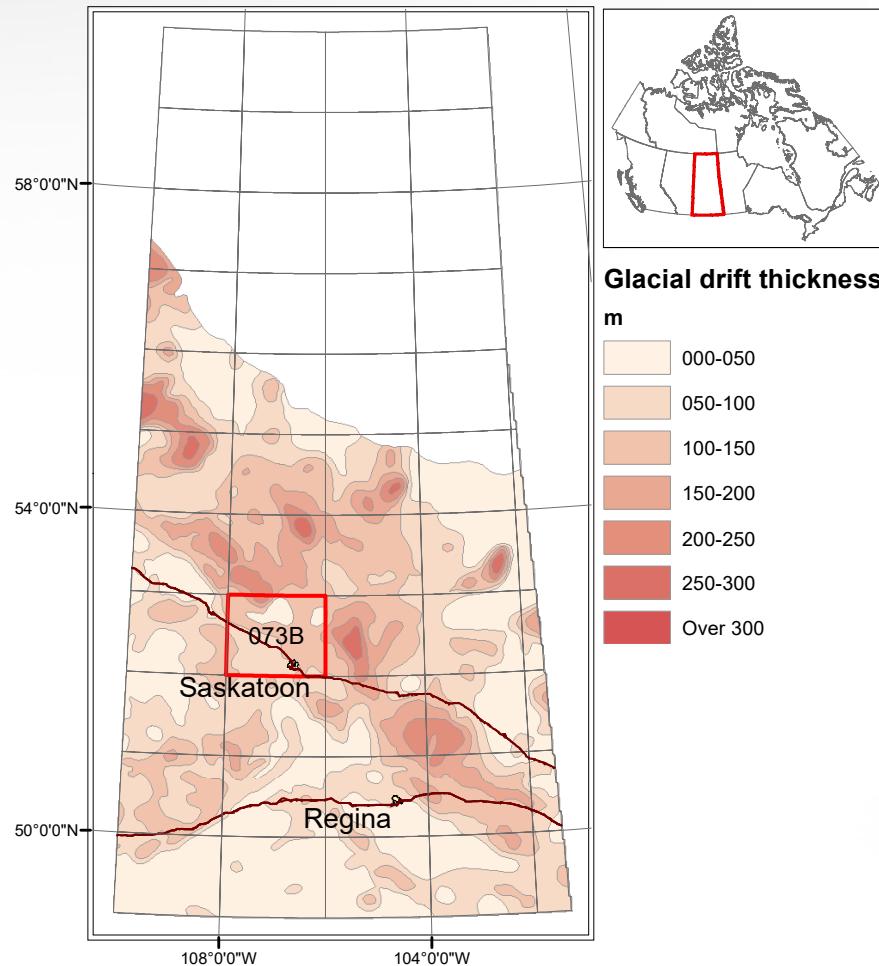
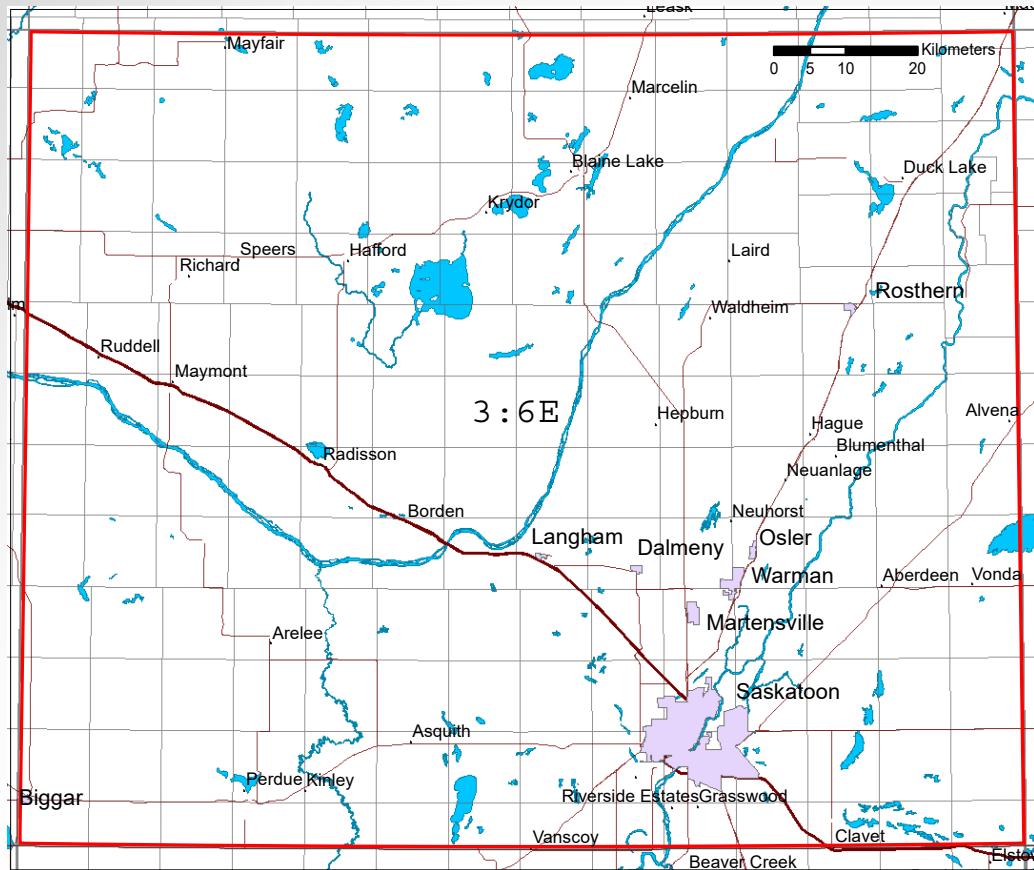
Epistemic uncertainty – how certain are we that we know what we know?

- Input parameters – Natural variation

How can uncertainty associated with natural variation be quantified and represented in a Groundwater Vulnerability Assessment?

Study Area

NTS Map Area 073B



Selecting GVA method – NTS Map Area 073B

Selection of groundwater vulnerability assessment method

1. Hydrogeologic setting
2. Availability of data
3. Purpose and product

Groundwater vulnerability assessment method	Source/citation	Year	Type of assessment method	Qualitative rating															
				Consideration of multiple overlying units	Hydraulic conductivity of overlying units	Depth to water, depth of overlying units (Net Recharge)	Aquifer media, lithology	Topography (percent slope)	Vadose zone effect	Hydraulic conductivity of aquifer	Precipitation	Fracturing, karst, preferential flow paths	Subsoil, surficial geology, lithology of overlying zones	Proximity of catchment, recharge zones	Hydraulic head loss between surface and aquifer	Temporal distribution of rainfall	Porosity of overlying units	Land use, plant cover	Confining conditions
DRASTIC	Aller et al.	1987	PCSM & HCS	Y			Y	Y	Y	Y									
SINTACS	Civita	1994	PCSM	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y					
AVI	Van Stempvoort et al.	1993	AR		Y	Y	Y												
ISI	Ontario MOE	2001	AR /RS		Y	Y	Y												
DAT	Ross et al.	2004	NUM			Y	Y	Y									Y	Y	
RTt	Oke et al.	2016	RS /AR			Y	Y				Y		Y					Y	
GOD	Foster et al.	1987	RS	Y			Y									Y			Y
EPIK	Doerfliger et al.	1999	PCMS	Y			Y			Y	Y				Y	Y	Y		Y
PI	Goldscheider et al.	2000	RS /MS	Y	Y	Y	Y	Y		Y				Y	Y	Y		Y	Y
COP	Vias et al.	2006	RS /MS	Y	Y		Y			Y	Y			Y	Y	Y	Y	Y	Y

Selecting GWVA method – NTS Map Area 073B

Selection of groundwater vulnerability assessment method

1. Hydrogeologic setting
2. Availability of data
3. Purpose and product

Captures processes

Suitable for low K tills

Used by Sk WSA

Deterministic

Groundwater vulnerability assessment method	Source/citation	Year	Type of assessment method															
			Qualitative rating	Consideration of multiple overlying units	Hydraulic conductivity of overlying units	Depth to water, depth of overlying units	(Net) Recharge	Aquifer media, lithology	Topography (percent slope)	Vadose zone effect	Hydraulic conductivity of aquifer	Precipitation	Fracturing, karst, preferential flow paths	Subsoil, surficial geology, lithology of overlying zones	Proximity of catchment recharge zones	Hydraulic head loss between surface and aquifer	Temporal distribution of rainfall	Porosity of overlying units
DRASTIC	Aller et al.	1987	PCSM & HCS	Y			Y	Y	Y	Y	Y							
SINTACS	Civita	1994	PCSM	Y	Y		Y	Y	Y	Y	Y	Y	Y					
AVI	Van Stempvoort et al.	1993	AR		Y	Y	Y											
ISI	Ontario MOE	2001	AR /RS		Y	Y	Y											
DAT	Ross et al.	2004	NUM			Y	Y	Y							Y	Y		
RTt	Oke et al.	2016	RS /AR			Y	Y				Y		Y				Y	
GOD	Foster et al.	1987	RS	Y			Y							Y				Y
EPIK	Doerfliger et al.	1999	PCMS	Y			Y				Y	Y		Y	Y	Y		Y
PI	Goldscheider et al.	2000	RS /MS	Y	Y	Y	Y	Y			Y			Y	Y	Y		Y
COP	Vias et al.	2006	RS /MS	Y	Y		Y			Y	Y			Y	Y	Y	Y	Y

AVI Method

Aquifer Vulnerability Index (AVI)

$$\text{Hydraulic resistance, } c(t) = \sum \frac{z_i(t)}{K_i(L/t)}$$

Depth, $z_i(t)$

Hydraulic conductivity, $K_i(L/t)$

$$\text{AVI} = \log_{10}(c)$$

c , Hydraulic Resistance (years)	Aquifer Vulnerability Index ($\log c$)	Vulnerability Color Codes
0 to 10	< 1	very high
10 to 100	1 to 2	high
100 to 1,000	2 to 3	moderate
1,000 to 10,000	3 to 4	low
> 10,000	> 4	very low

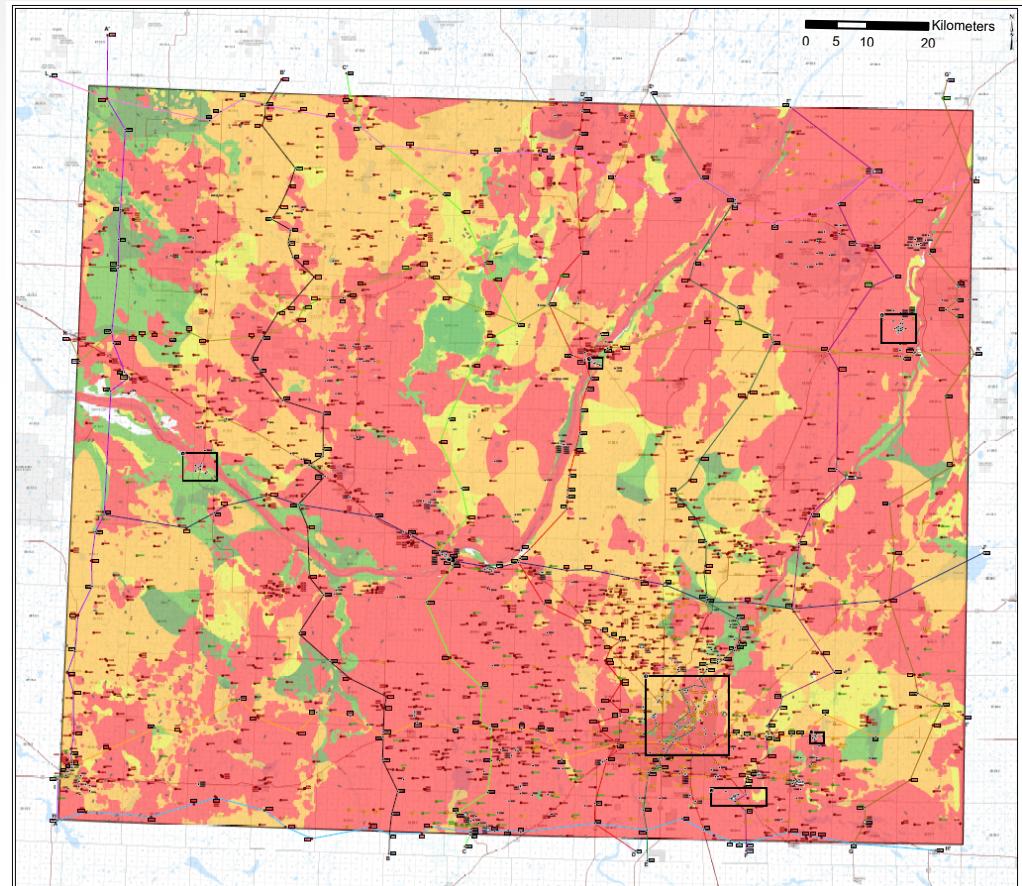


Image from: MDH 2011. Hydrogeologic mapping of NTS Mapsheet Saskatoon 73B; M1890. Aquifer Vulnerability Index to top of first potential mappable aquifer 73B NTS Mapsheet

Characterization of K in Saskatchewan tills

Hydraulic conductivity, K

Stratigraphic K

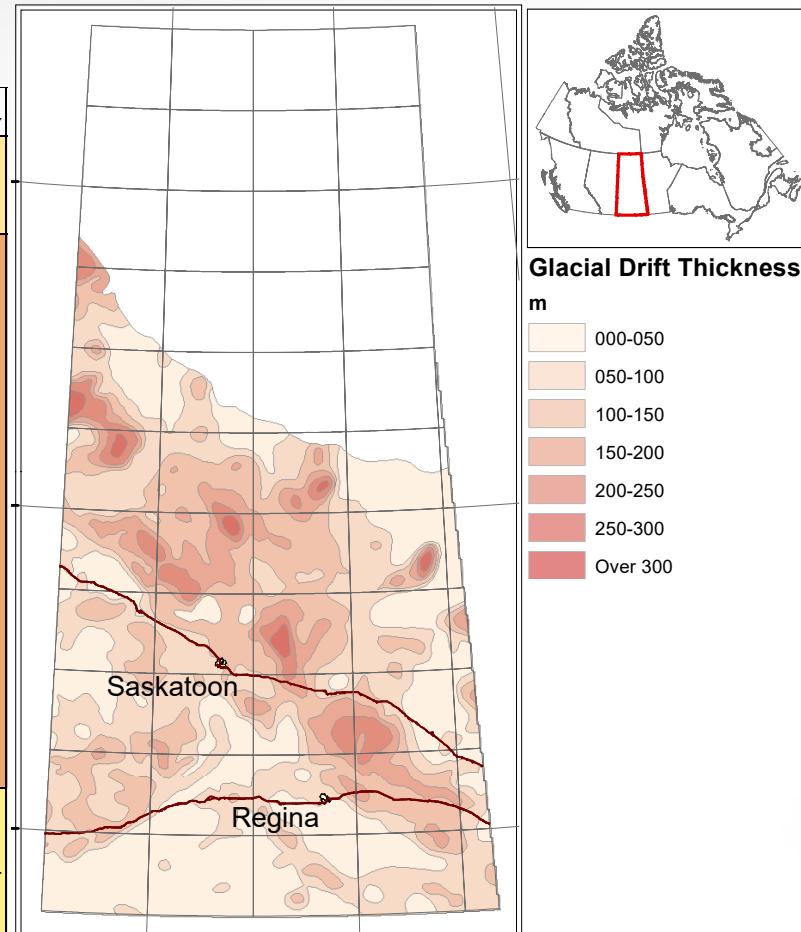
Group	Aquifer Unit	Hydraulic Conductivity (m/s)
Saskatoon Group	Battleford Till	1.0E-07
	Upper Floral Till	1.0E-08
	Lower Floral Till	1.0E-09
	Basal Floral Till	1.0E-09
Sutherland Group	Warman Till	1.0E-10
	Upper Dundurn Till	1.0E-10
	Lower Dundurn Till	1.0E-10
	Basal Dundurn Till	1.0E-10
	Upper Mennon Till	1.0E-10
	Lower Mennon Till	1.0E-10
Bearpaw Formation	Aquadell Mb Shale	1.0E-11
	Snakebite Mb Shale	1.0E-11
	Beachy Mb Shale	1.0E-11

MDH Engineered Solutions Corp. 2010. Procedures for regional hydrogeologic mapping.
Prepared for the Saskatchewan Watershed Authority. M1890-1030109.

Characteristics of K in tills

- Range of values?
- Distribution?
- Relationship w/ depth?

PERIOD	EPOCH	GROUP	FORMATION	LITHOLOGY
Quaternary	Holocene	Saskatoon	Surficial Stratified Deposits	Stratified Drift
			Battleford	Glacial till & intertill deposits
			Floral	
			Warman	
	Pleistocene	Sutherland	Dundurn	
			Mennon	
			(Quaternary Empress Gp)	Pre and Proglacial Deposits
	Neogene		(Tertiary Empress Gp)	
Tertiary				

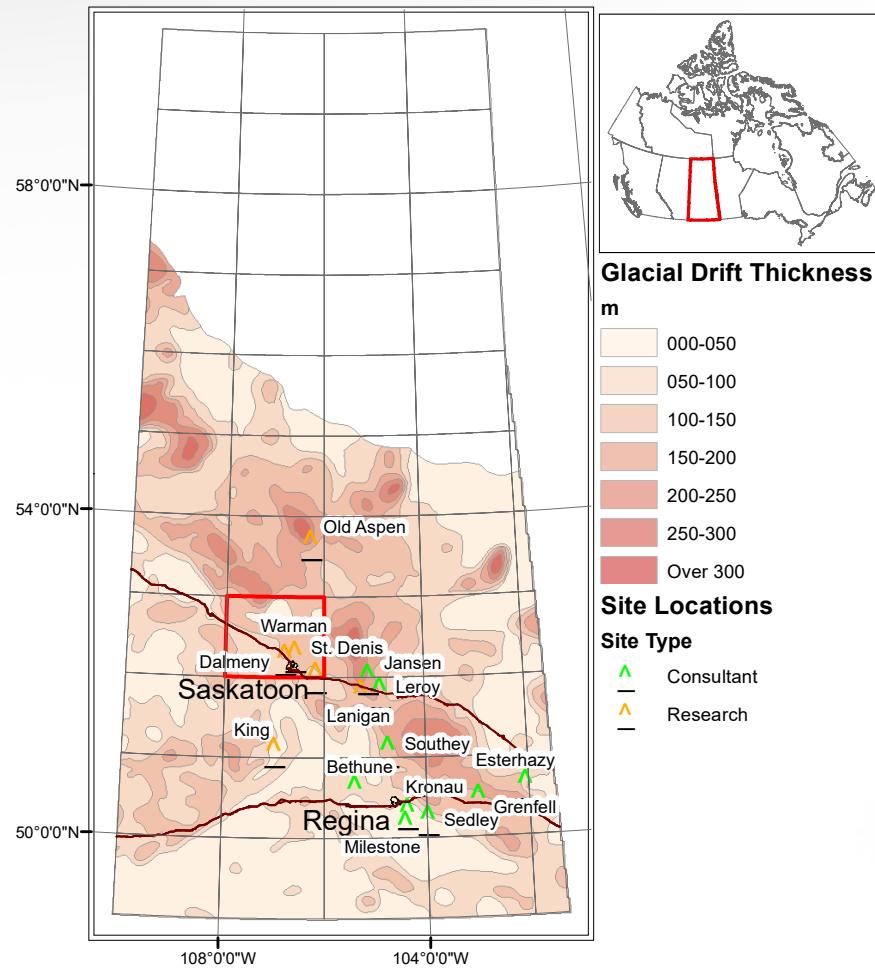


Characterization of K in Saskatchewan tills

K Database

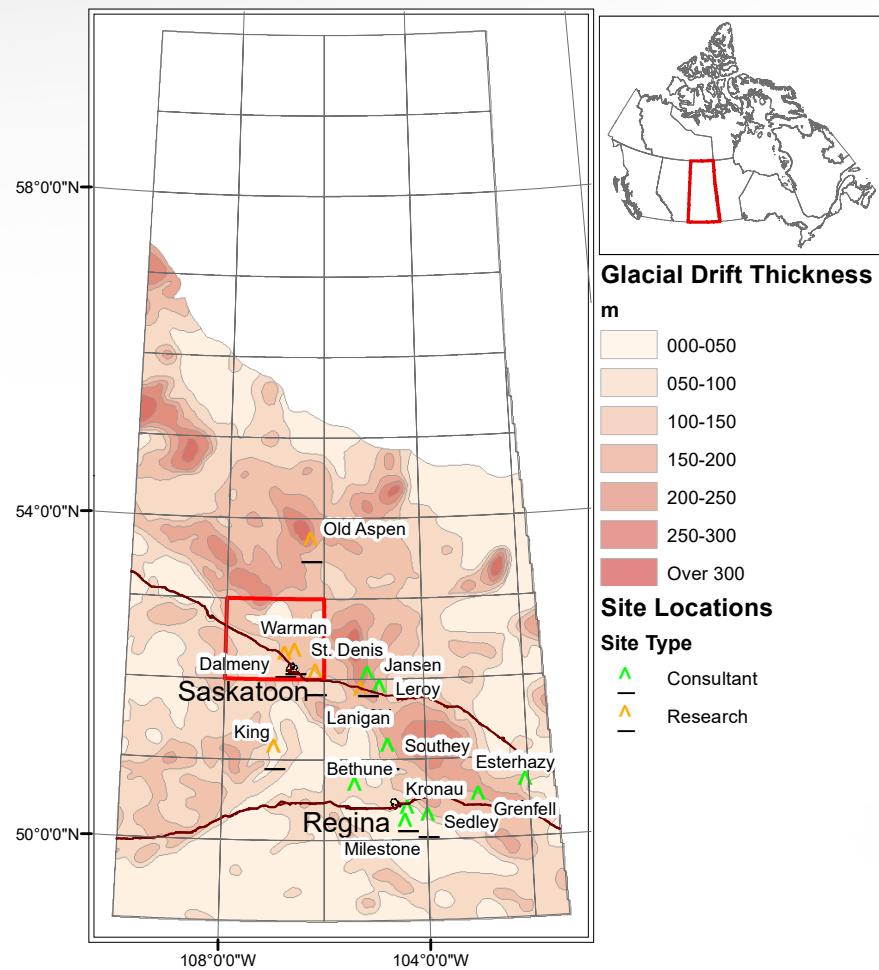
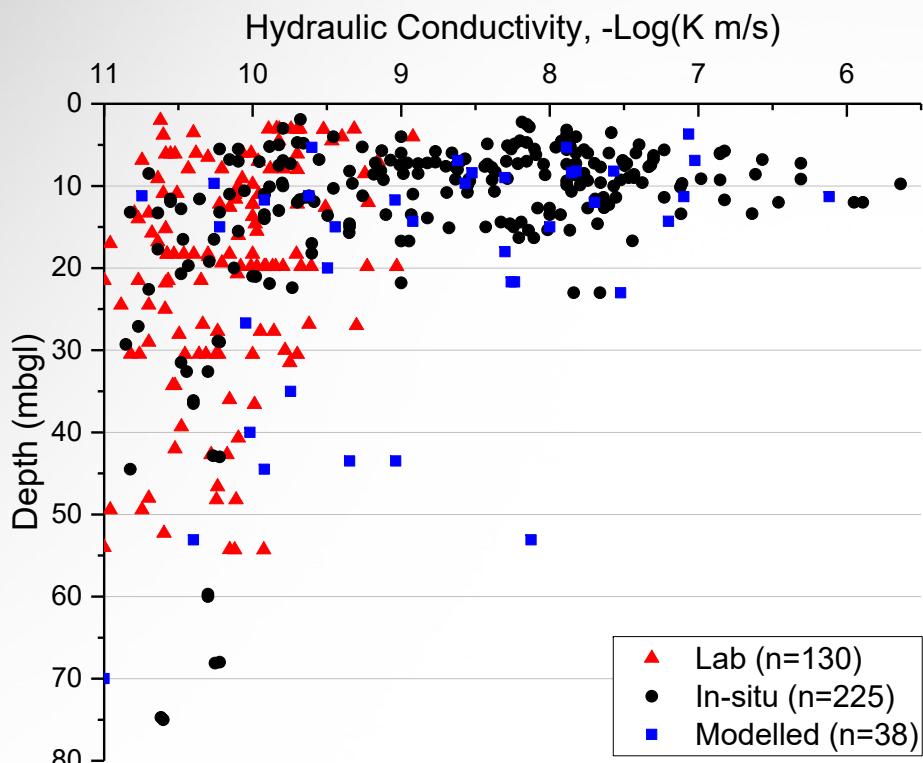
Lab data (n=130)
In-situ (n=225)
Model (n=38)

Site Name	Source	Data
Bethune	Golder Associates 2010	4
Dalmeny	Keller et al. 1986	14
	Keller et al. 1988	40
	Fortin et al. 1991	1
Esterhazy	MDH Solutions 2010	2
Grenfell	SNC-Lavalin 2018b	37
Jansen	MDH Solutions 2010b	45
King	Barbour et al. 2012	1
	Boldt-Leppin and Hendry 2003	15
	Shaw 1997	30
	Harrington et al. 2007	28
Kronau	Golder Associates 2013b	3
Lanigan	Boldt-Leppin and Hendry 2003	12
	Kelln 2001	49
Leroy	SNC-Lavalin 2009	29
Milestone	Golder Associates 2013	3
Old Aspen	Anochikw a et al. 2012	1
Sedley	SNC-Lavalin 2018	15
Southey	Golder Associates 2016	1
St. Denis	Hayashi 1996	20
Warman	Keller et al. 1988	19
	Keller et al. 1989	23
	Remenda et al. 1996	1
15 Sites	21 Reports	(8 R, 9 C, 4 T) 393



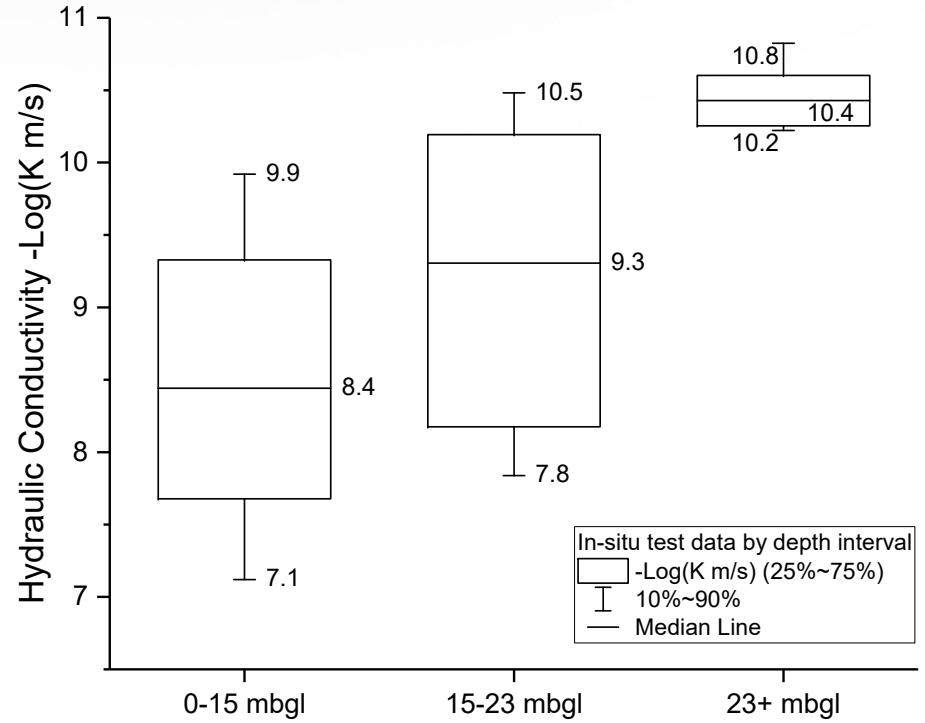
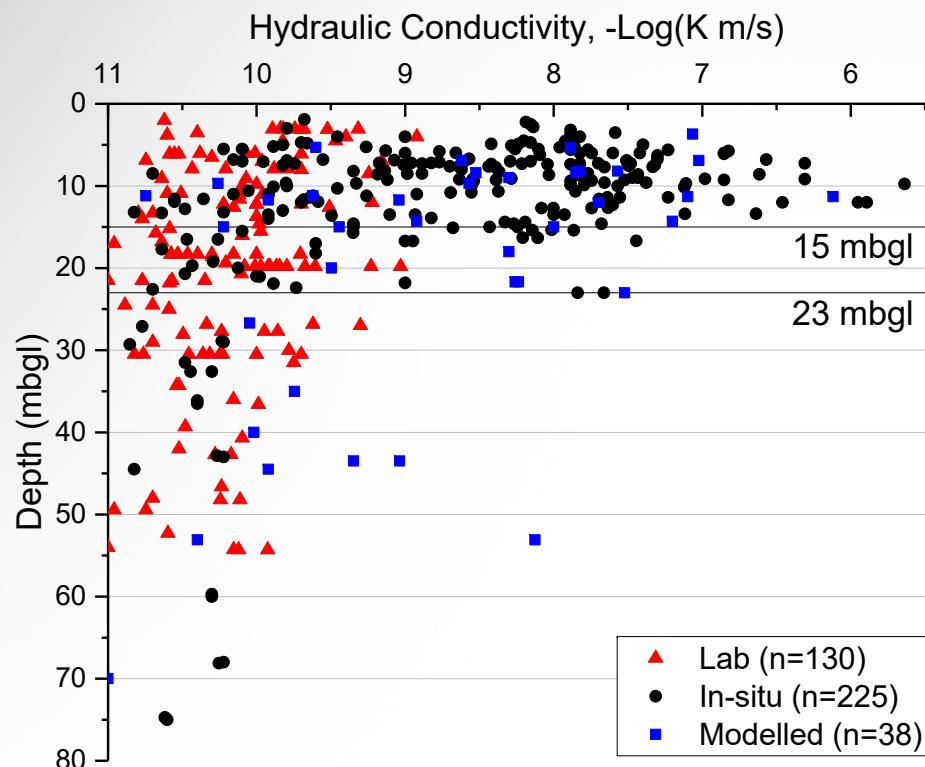
Characterization of K in Saskatchewan tills

K Database – Analysis



Characterization of K in Saskatchewan tills

K Database – Depth-defined intervals



Characterization of K in Saskatchewan tills

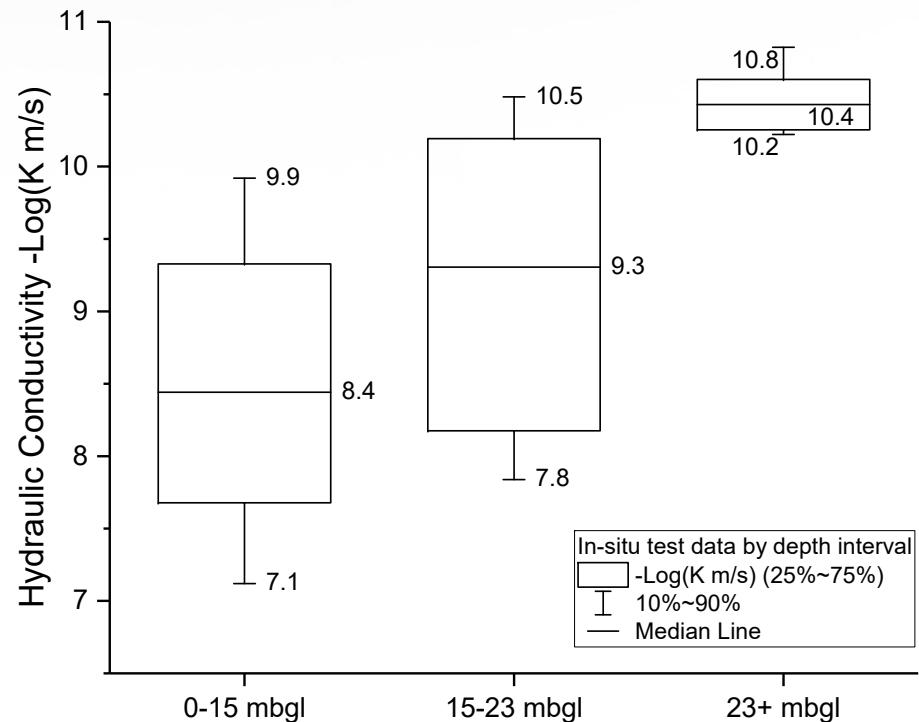
K Database – Statistical Characterization

Three set of depth-defined K values: P10, Mean, P90

10th Percentile, P10 (Conservative)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	7.6E-08
15-23 mbgl	1.5E-08
>23 mbgl	6.0E-11

Geometric Mean, M (Expected)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	3.6E-09
15-23 mbgl	5.0E-10
>23 mbgl	3.7E-11

90th Percentile, P90 (Optimistic)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	1.2E-10
15-23 mbgl	3.3E-11
>23 mbgl	1.5E-11



Case Study AVI – NTS Map Area 073B

“Classic” AVI

Group	Aquitard Unit	Hydraulic Conductivity (m/s)
Saskatoon Group	Battleford Till	1.0E-07
	Upper Floral Till	1.0E-08
	Lower Floral Till	1.0E-09
	Basal Floral Till	1.0E-09
Sutherland Group	Warman Till	1.0E-10
	Upper Dundurn Till	1.0E-10
	Lower Dundurn Till	1.0E-10
	Basal Dundurn Till	1.0E-10
	Upper Mennon Till	1.0E-10
	Lower Mennon Till	1.0E-10
Bearpaw Formation	Aquadell Mb Shale	1.0E-11
	Snakebite Mb Shale	1.0E-11
	Beachy Mb Shale	1.0E-11

MDH Engineered Solutions Corp. 2010. Procedures for regional hydrogeologic mapping. Prepared for the Saskatchewan Watershed Authority. M1890-1030109.

$$c(9704) = \frac{z_{Battleford}}{K_{Battleford}} + \frac{z_{Upper\ Floral}}{K_{Upper\ Floral}} + \frac{z_{Lower\ Floral}}{K_{Lower\ Floral}} = \frac{4.87\ m}{10^{-7}\ m/s} + \frac{29.88\ m}{10^{-8}\ m/s} + \frac{1.82\ m}{10^{-9}\ m/s}$$

$$c = 154\ years$$

$$AVI = \log_{10}(154) = 2.2$$

- WSA Borehole database

- 2700 boreholes

- At each borehole:

- c calculated for each stratigraphic unit
- c summed to top of first possible aquifer

Example:

Borehole 9704

First possible aquifer: Lower Floral Aq



Depth-defined AVI

10th Percentile, P10 (Conservative)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	7.6E-08
15-23 mbgl	1.5E-08
>23 mbgl	6.0E-11

Geometric Mean, M (Expected)	
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>23 mbgl	1.5E-11

➤ WSA Borehole database

➤ 2700 boreholes

➤ At each borehole:

- Find depth to top of first possible aquifer
- Sum c for depth-defined intervals for P10, Mean, P90

Example:

Borehole 9704

First possible aquifer: Lower Floral Aq (34.75 m)

$$c(9704) = \frac{15 \text{ m}}{K_{0-15 \text{ mbgl}}} + \frac{(23 - 15) \text{ m}}{K_{15-23 \text{ mbgl}}} + \frac{(z-23) \text{ m}}{K_{>23 \text{ mbgl}}} = \frac{15 \text{ m}}{7.6 \times 10^{-8} \text{ m/s}} + \frac{8 \text{ m}}{1.5 \times 10^{-8} \text{ m/s}} + \frac{(34.75 - 23) \text{ m}}{6.0 \times 10^{-11} \text{ m/s}}$$

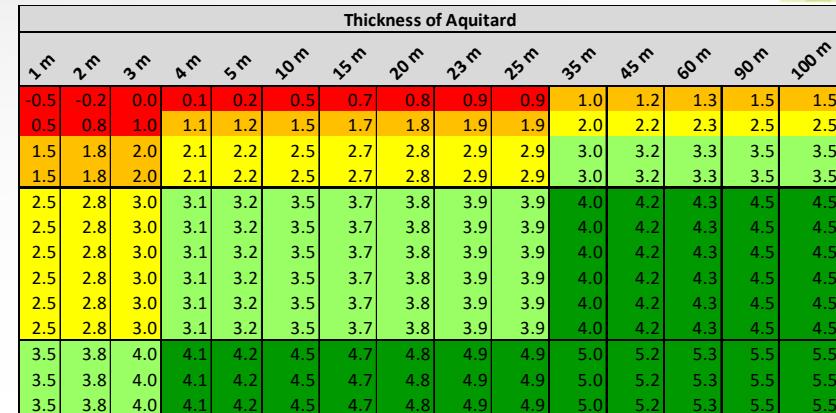
$$c_{P10} = 7,195 \text{ years}$$

$$AVI_{P10} = \log_{10}(7,195) = 3.9$$

Case Study AVI – NTS Map Area 073B

“Classic” AVI

Group	Aquitard Unit	Hydraulic Conductivity (m/s)
Saskatoon Group	Battleford Till	1.0E-07
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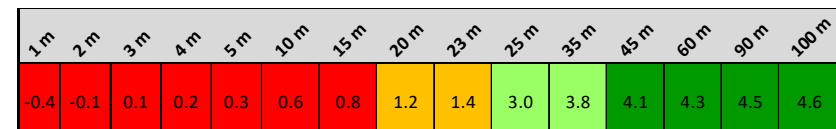


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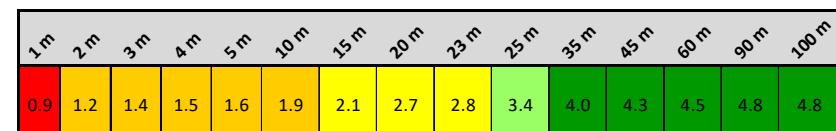
Depth-defined AVI

$$c(t) = \sum \frac{z_i(t)}{K_i(L/t)}$$

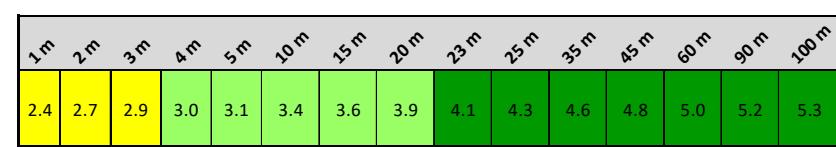
10th Percentile, P10 (Conservative)	
Depth	Hydraulic Conductivity (m/s)
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Geometric Mean, M (Expected)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	3.6E-09
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>23 mbgl	3.7E-11



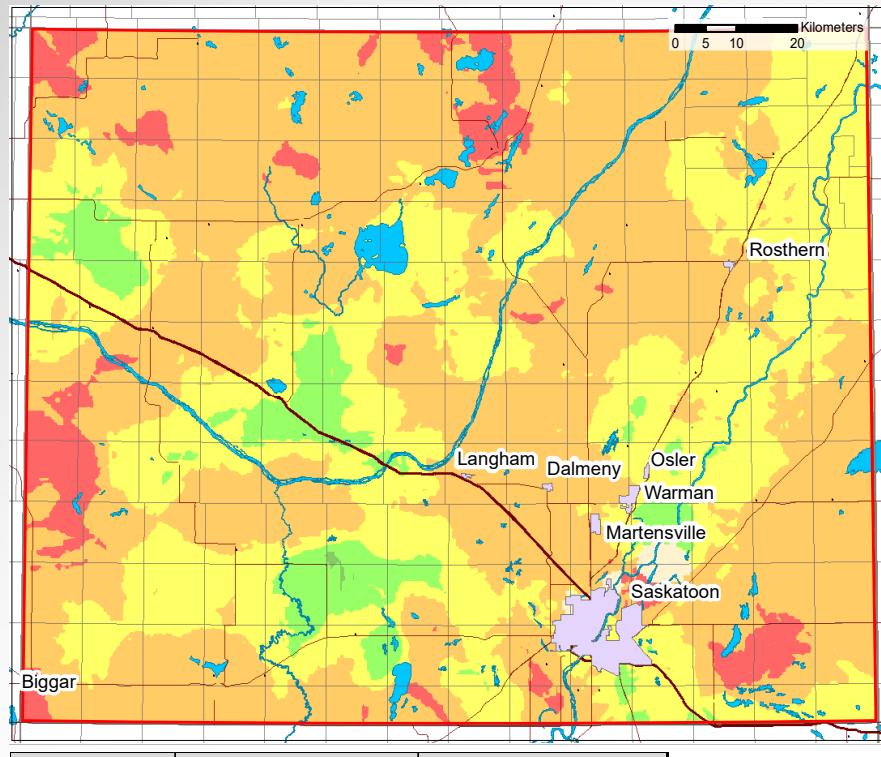
90th Percentile, P90 (Optimistic)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	1.2E-10
15-23 mbgl	3.3E-11
>23 mbgl	1.5E-11



c, Hydraulic Resistance (years)	Aquifer Vulnerability Index (Log)	Vulnerability Color Codes
0 to 10	< 1	very high
10 to 100	1 to 2	high
100 to 1,000	2 to 3	moderate
1,000 to 10,000	3 to 4	low
> 10,000	> 4	very low

Case Study AVI – NTS Map Area 073B

“Classic” AVI



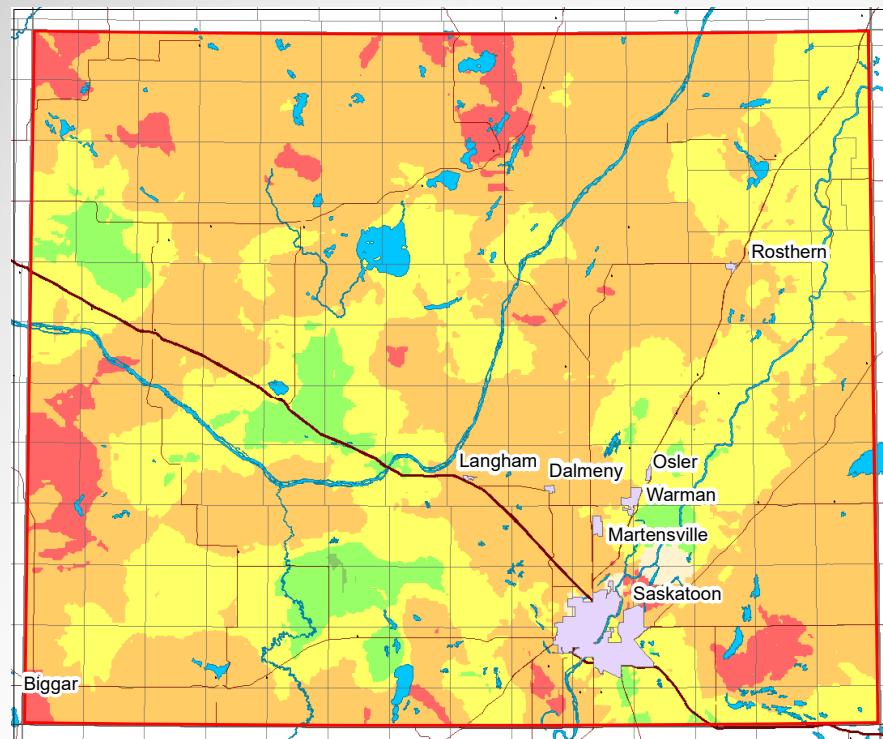
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> 10,000	> 4	very low

➤ ArcGIS

- Borehole database with AVI values
- Point AVI -> Raster
 - Ordinary Krigging

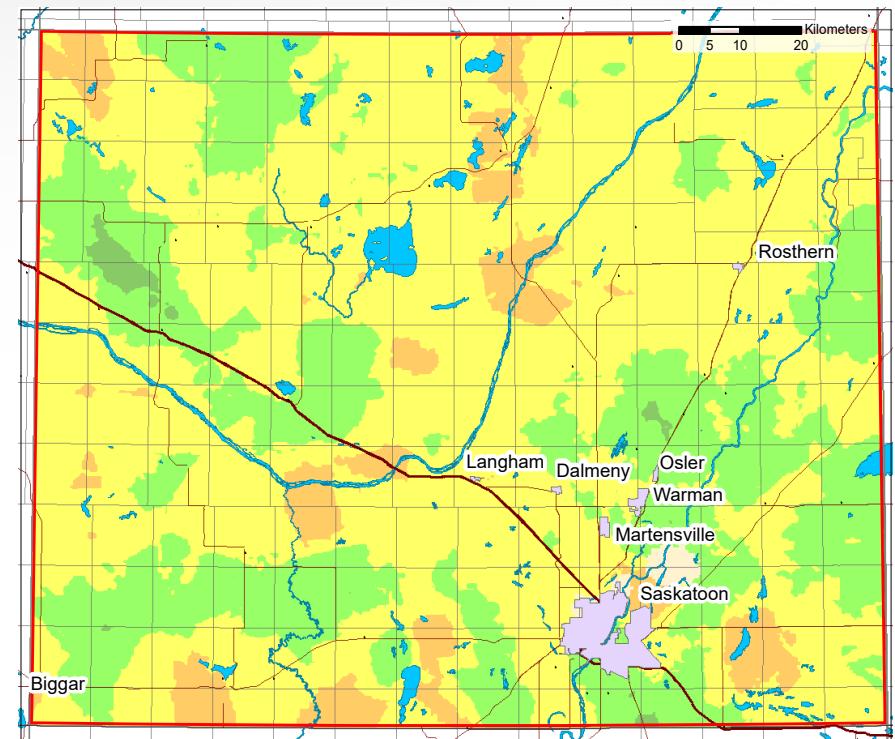
Case Study AVI – NTS Map Area 073B

“Classic” AVI



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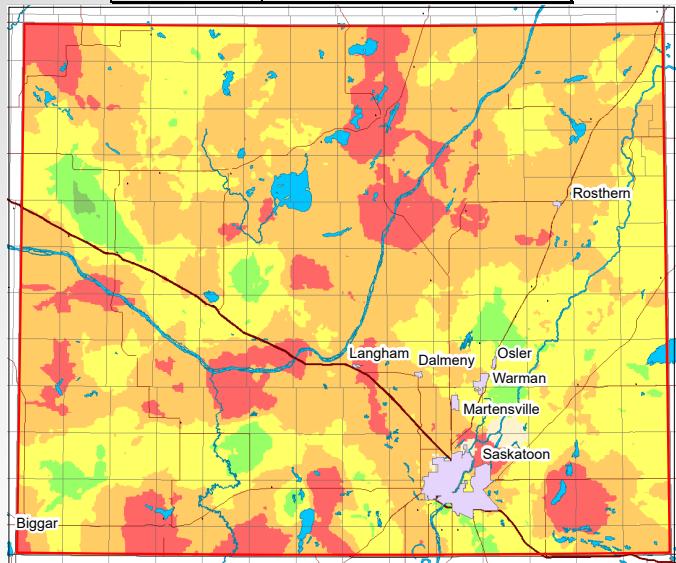
Mean (Depth-defined) AVI



Case Study AVI – NTS Map Area 073B

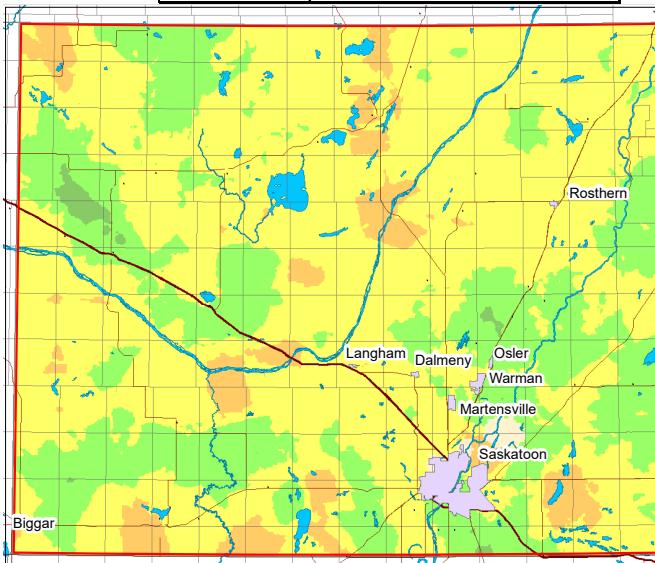
P10 (Depth) AVI

10th Percentile, P10 (Conservative)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	7.6E-08
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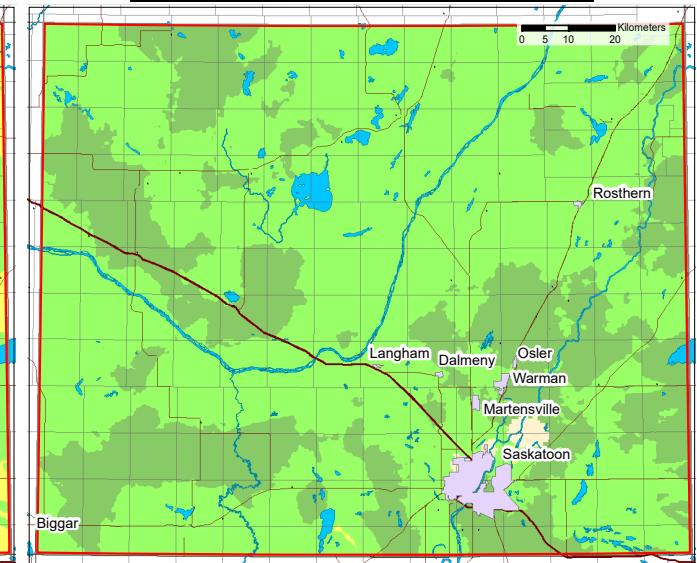
Mean (Depth) AVI

Geometric Mean, M (Expected)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	3.6E-09
15-23 mbgl	5.0E-10
>23 mbgl	3.7E-11



P90 (Depth) AVI

90th Percentile, P90 (Optimistic)	
Depth	Hydraulic Conductivity (m/s)
0-15 mbgl	1.2E-10
15-23 mbgl	3.3E-11
>23 mbgl	1.5E-11

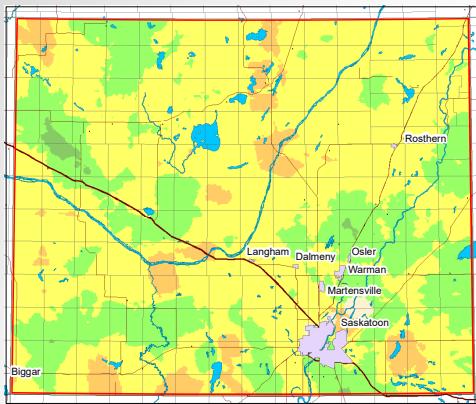


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1,000 to 10,000	3 to 4	low
> 10,000	> 4	very low

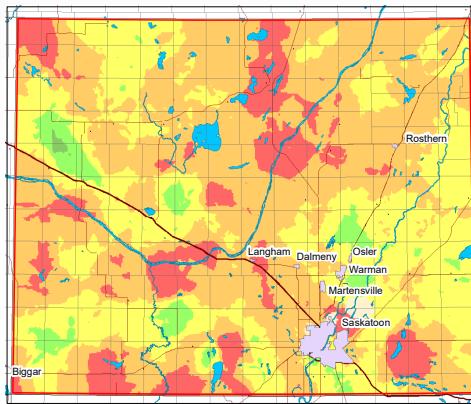
Case Study AVI – NTS Map Area 073B

Uncertainty: Residuals

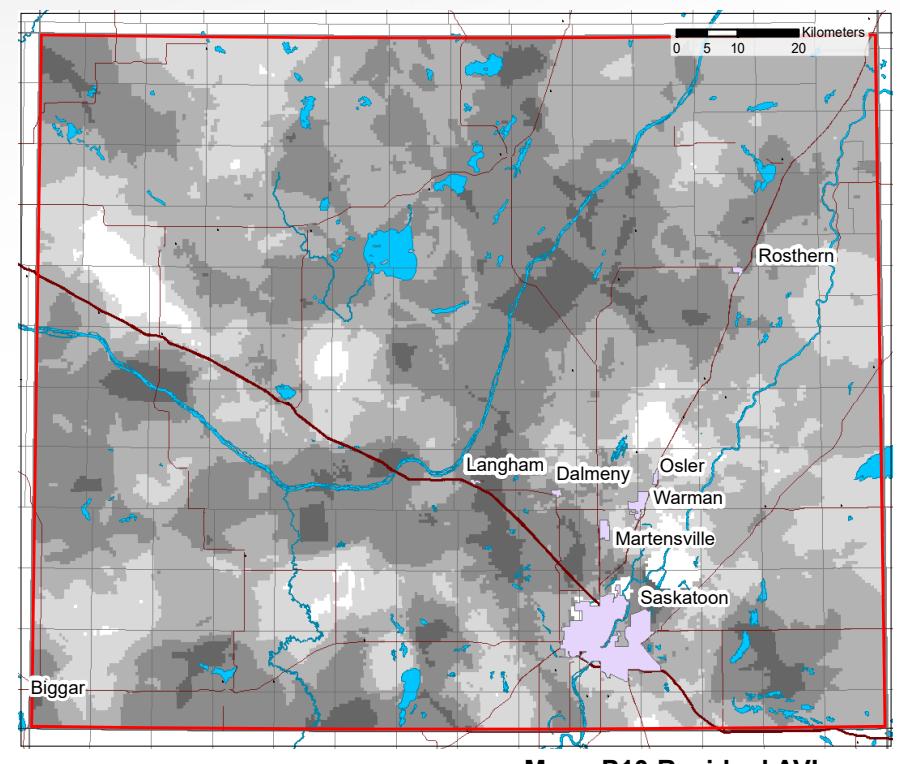
Mean AVI



P10 AVI



Mean-P10 AVI Residuals



c, Hydraulic Resistance (years)	Aquifer Vulnerability Index (Log _c)	Vulnerability Color Codes
0 to 10	< 1	very high
10 to 100	1 to 2	high
100 to 1,000	2 to 3	moderate
1,000 to 10,000	3 to 4	low
> 10,000	> 4	very low



Future Work

Immediate plans:

- Analysis of AVI raster maps – meaningful correlations?
- Method of presentation – AVI and uncertainty displayed simultaneously

Possible directions of research:

- Validation of relative groundwater vulnerability values
- Investigate linguistic uncertainty

Take Away

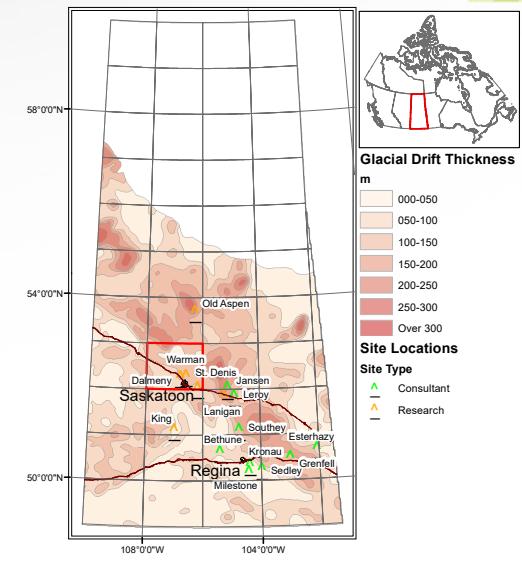
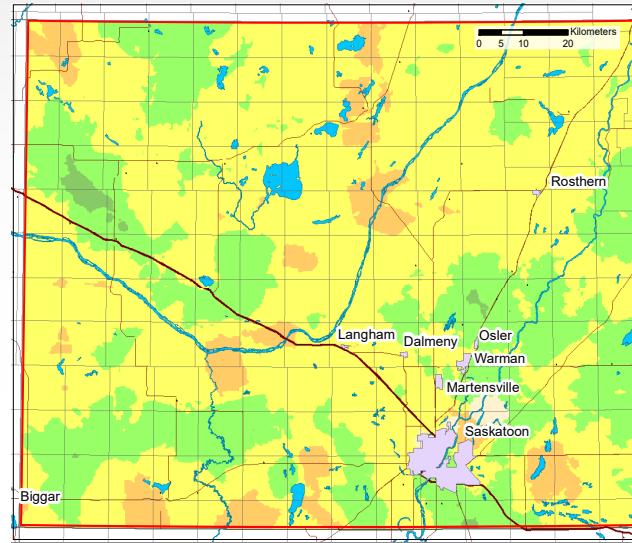
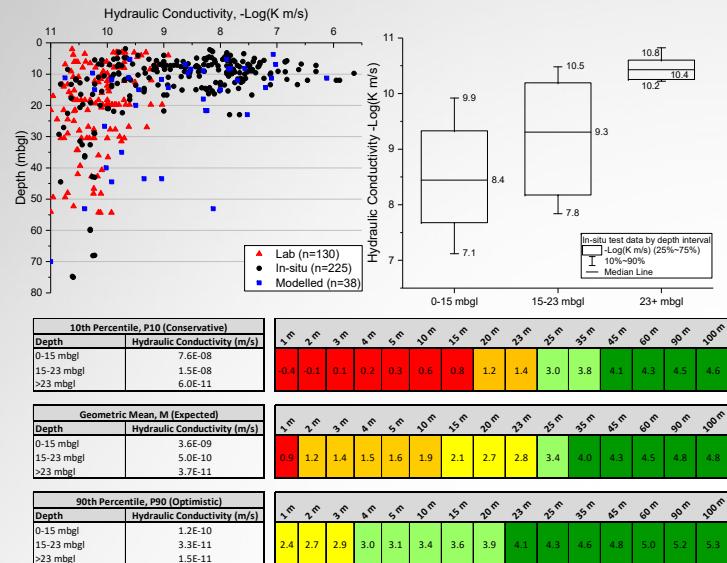
GVA valuable tools for groundwater management, policy, and education

GVA methods must be selected carefully

- Highly subjective
- Understand and communicate what is being represented

Opportunity to incorporate and represent uncertainty

Questions



Thank You

With special thanks to:
Saskatchewan Water Security Agency
Sylvia Fedoruk Canadian Centre for Nuclear Innovation



Representing uncertainty in groundwater vulnerability assessments – Ferris and Ferguson 2018



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