International Association of Hydrogeologists (IAH/AIH)

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Stable Isotopes and Hydrogeology in Ireland

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December 4th 2018

Outline

1. Stable isotope hydrology and “isoscapes”
2. Pathogens and subsurface transport
3. O^{18} isoscape for Ireland and geospatial drivers
4. Pathogen ingress mechanisms
5. Work to complete and direction

Stable Isotopes

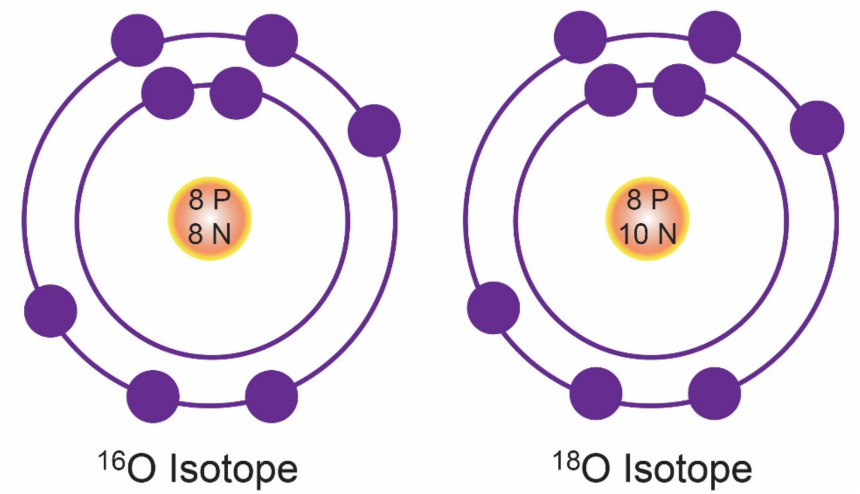
Stable isotopes

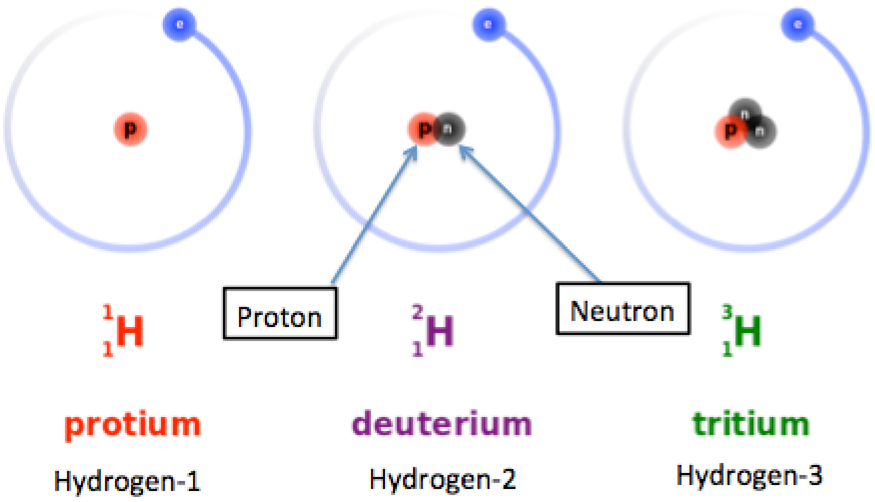
- Same atomic number – but different atomic weight due to varying numbers of neutrons in nucleus

- Stable isotopes – not involved in any natural radioactive decay process

- Naturally occurring

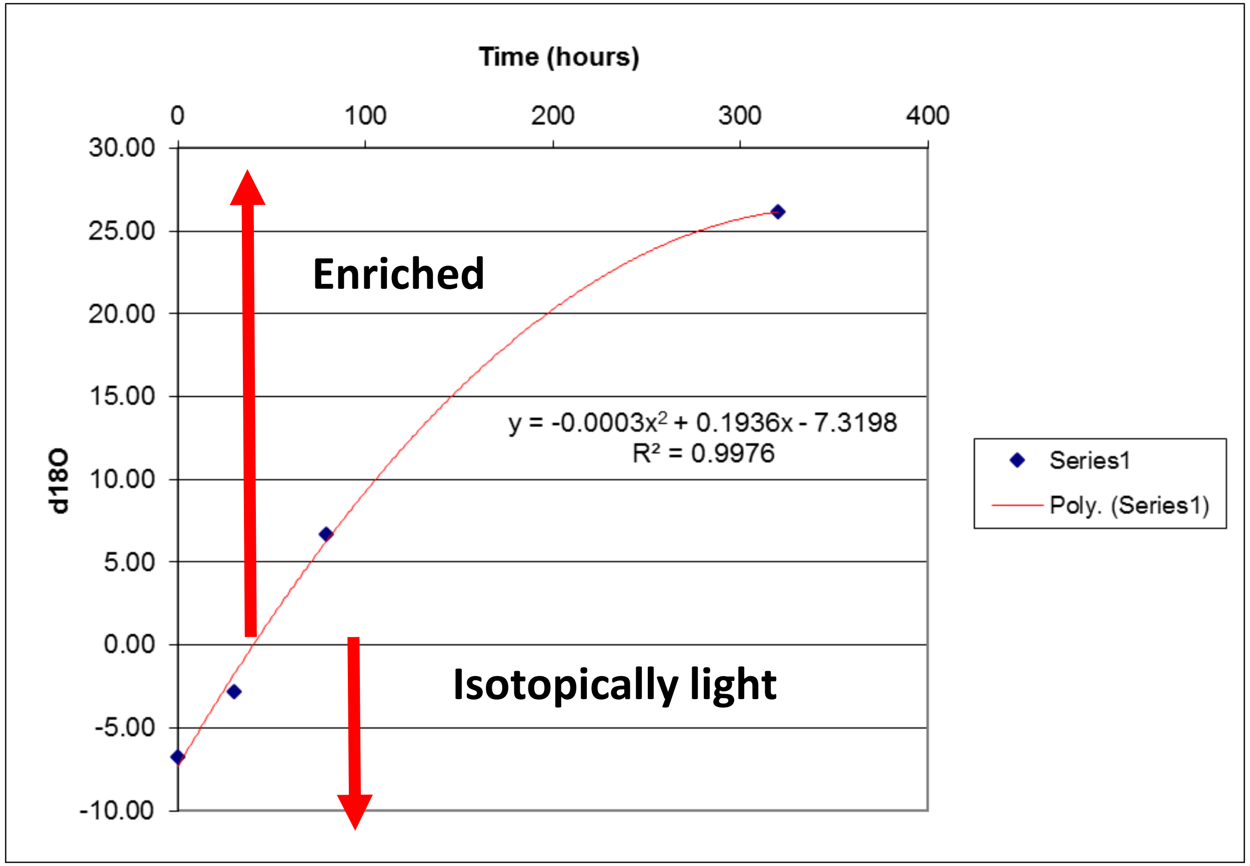
Used to study geologic processes that affect ground and surface water





Stable isotopes

- Fractionate into light and heavy fractions
- Mainly due to evaporation or heating
- One isotope much more common than other (large difference in mass)



Heavy O isotope

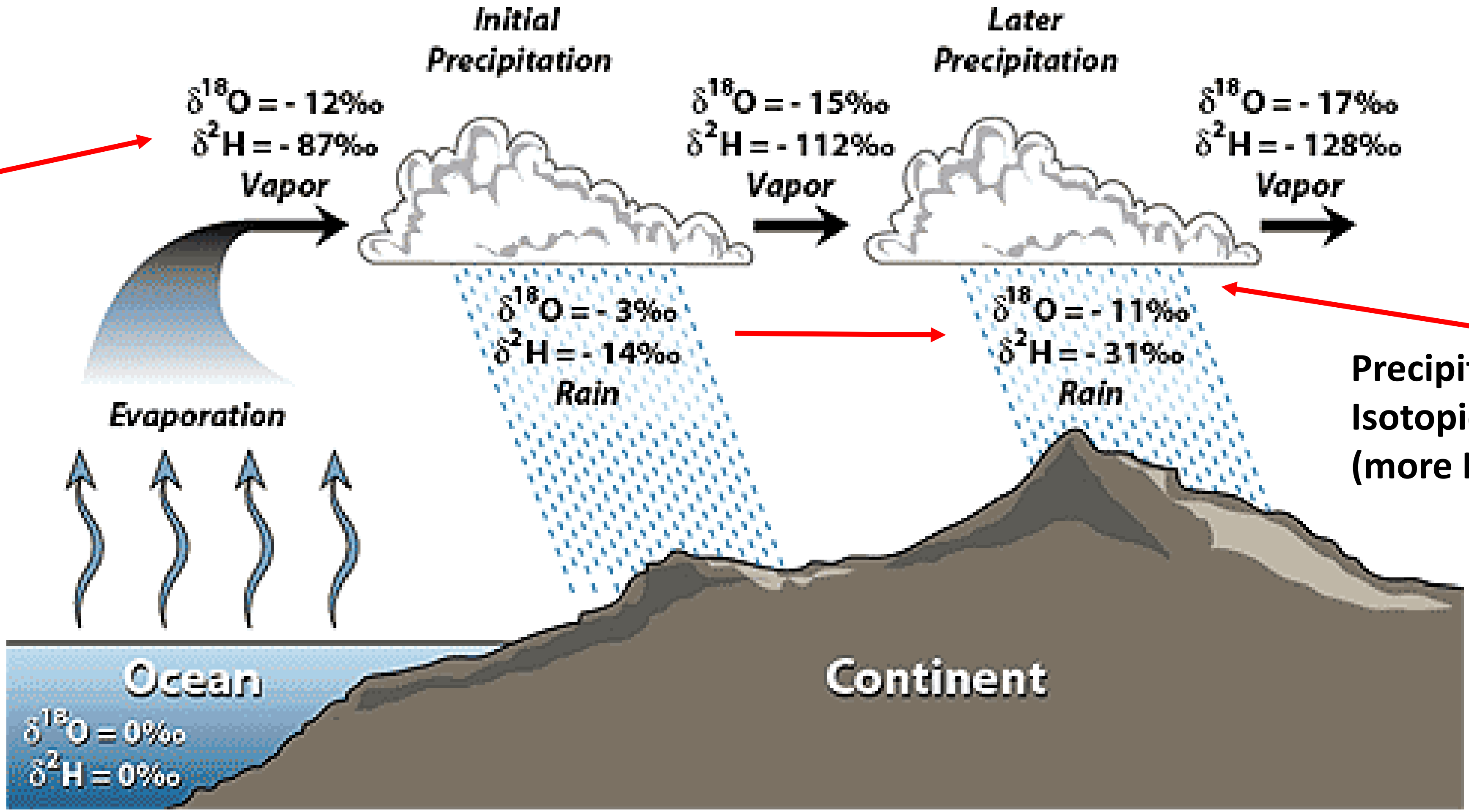
$$\boxed{\delta}^{18}O = \left(\frac{\left(\frac{\boxed{^{18}O}}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{\boxed{standard}}} - 1\right) * 1000\ \boxed{^{o}/_{oo}}$$

“del”

‘SMOW’

“permil”

Stable isotopes



Isotopically lighter than water left behind in ocean

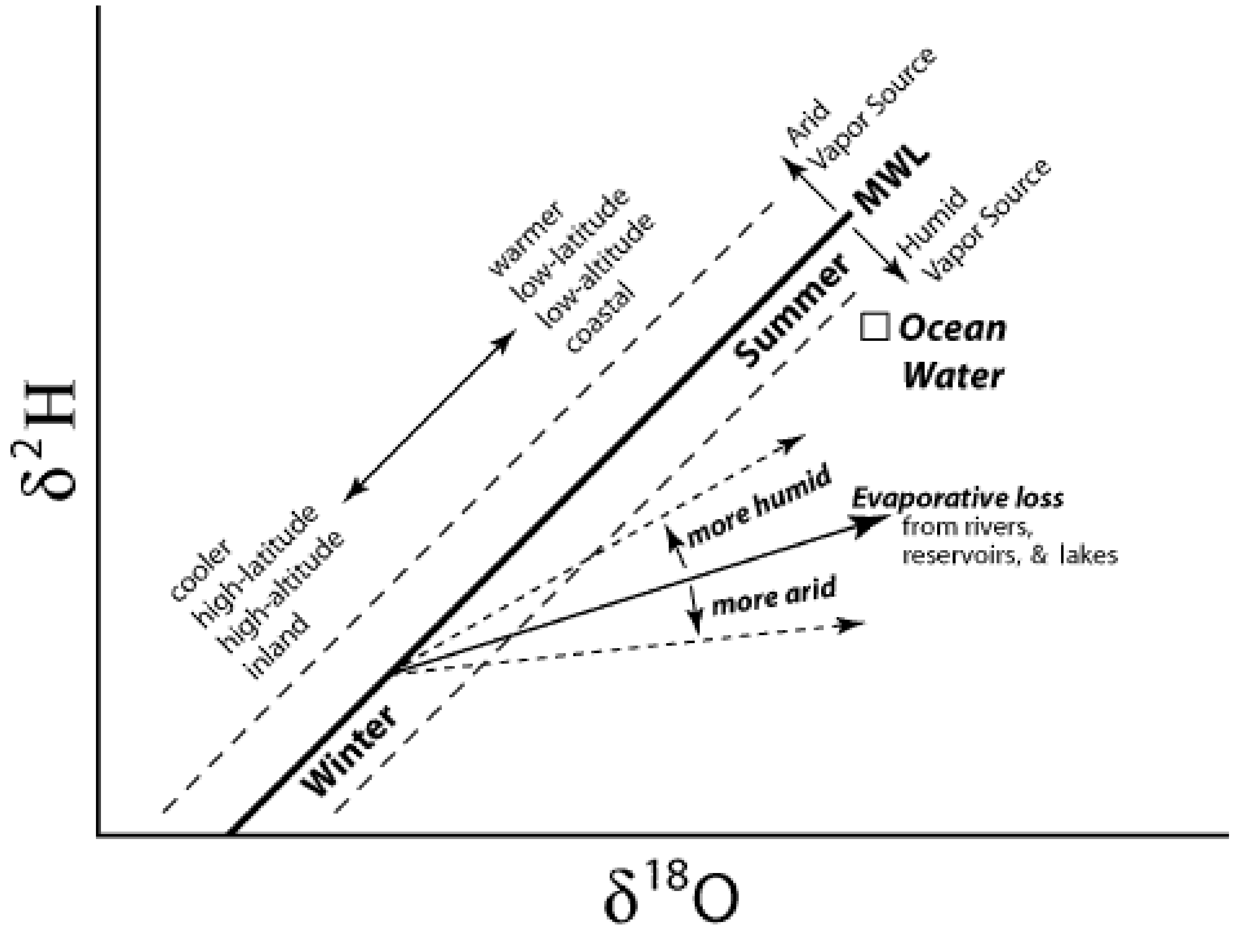
Precipitation Isotopically heavier (more H^2 and O^{18})

Stable isotopes

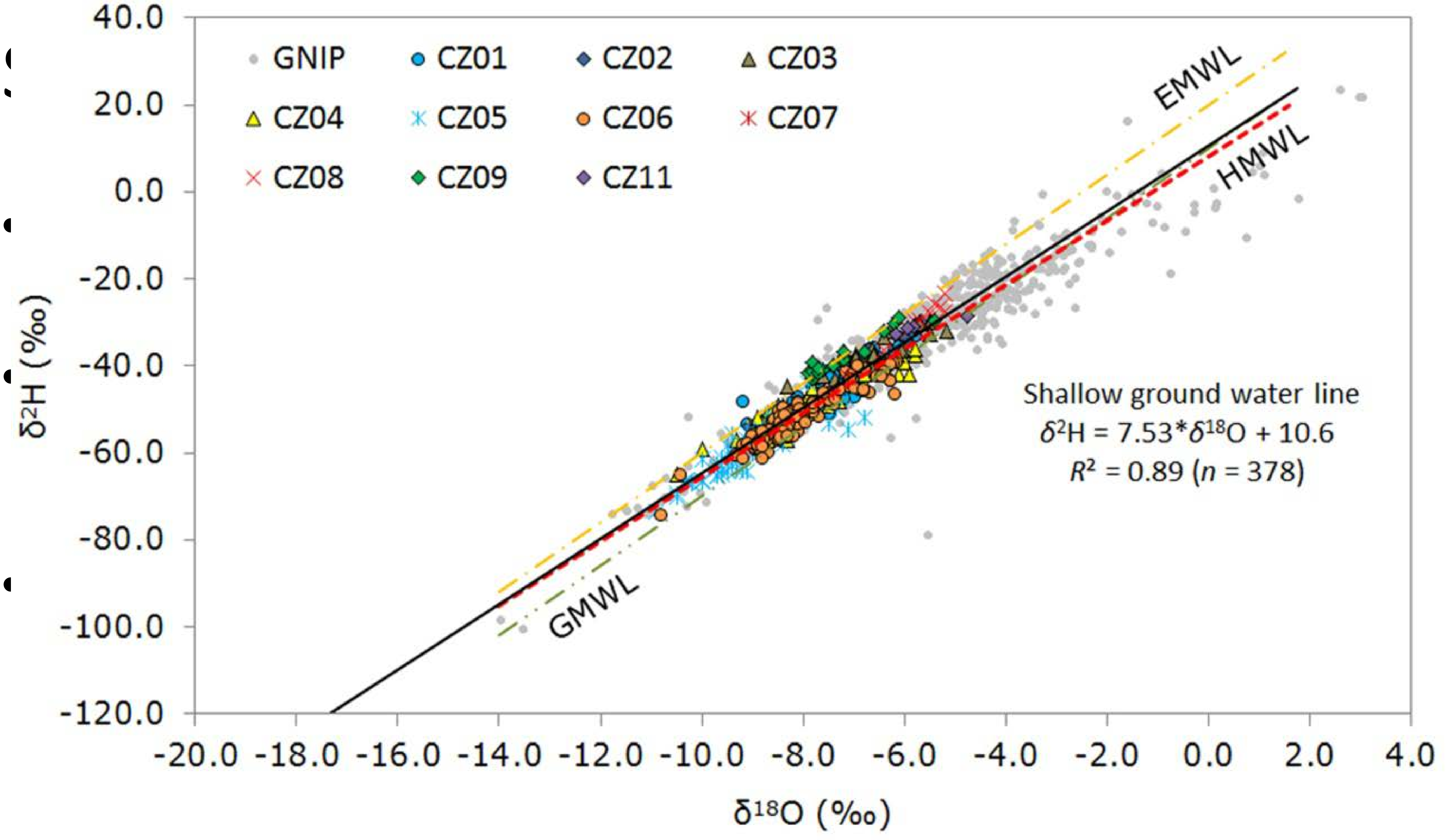
Composition affected only by physical processes

Temperature dependence – history

- Global meteoric water line
- Ocean water falls below line – isotopically enriched
- Deviations from MWL – changes in precipitation in warmer or colder climate or geochemical (geothermal water)



cesses



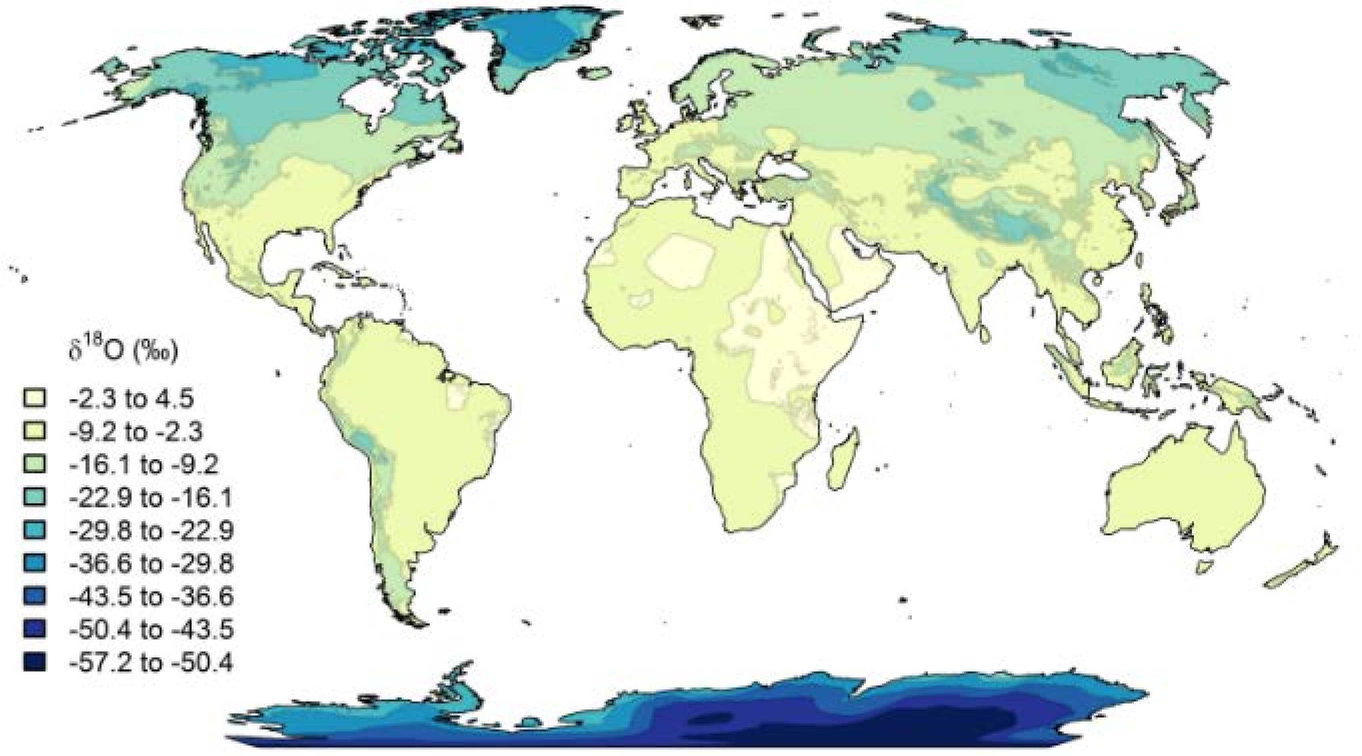
ource

e loss
ers,
rs, & lakes

Matiatos and Wassenaar (2018, JoH)

"Isoscapes"

- Describes large-scale spatiotemporal stable isotope distributions within natural environments
- Investigates the hydrological connectivity between water resource and hydro-climatic sources
- Large scale mapping of the stable isotopic composition of phreatic aquifers are used as a proxy for revealing recharge zones to enable sustainable management of water resources



http://wateriso.utah.edu/waterisotopes

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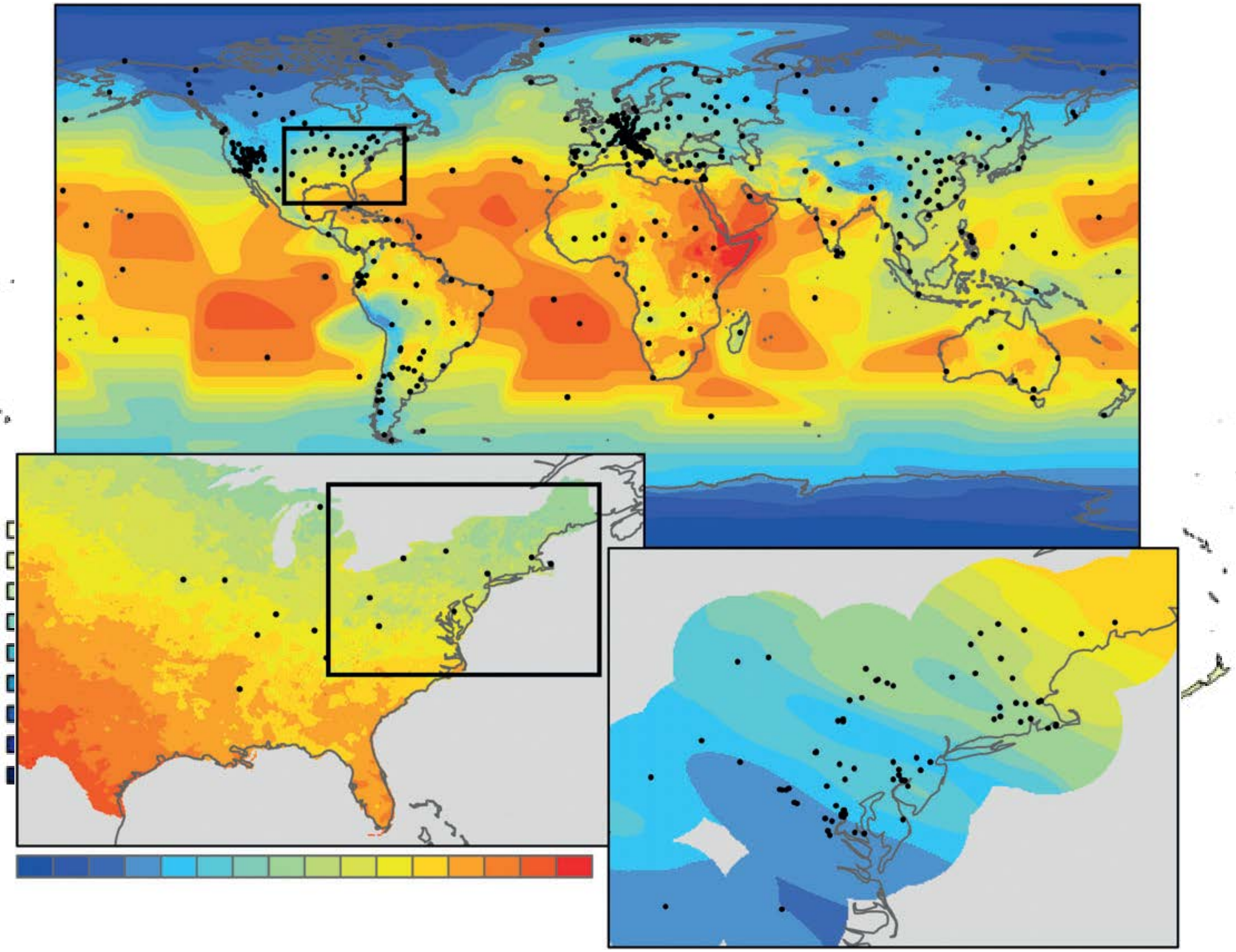


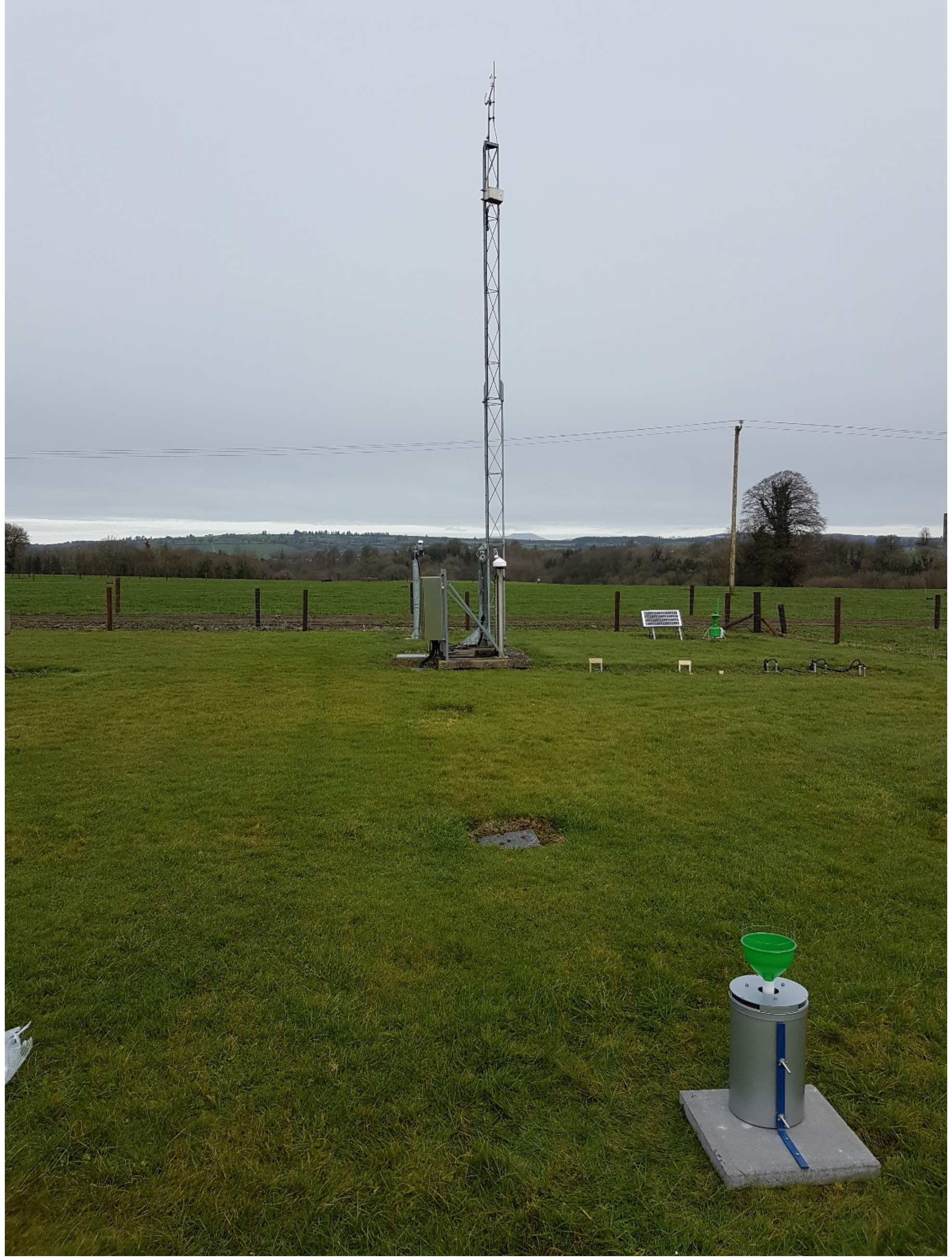
http://wateriso.utah.edu/waterisotopes

ISO-MECH

- First temporal O^{18} and D groundwater isoscapes for Ireland
- Sampled EPA groundwater monitoring network (> 290 sites) – 2 periods (plus 2013 study)
- Plus domestic well study areas utilised in on-going pathogen studies

ISO-MECH

- Insufficient spatial coverage for isotopes in precipitation hinders investigations of relationship between ground water and precipitation
- Need information to help quantify aquifer replenishment rates
- Installed rain collector gauges



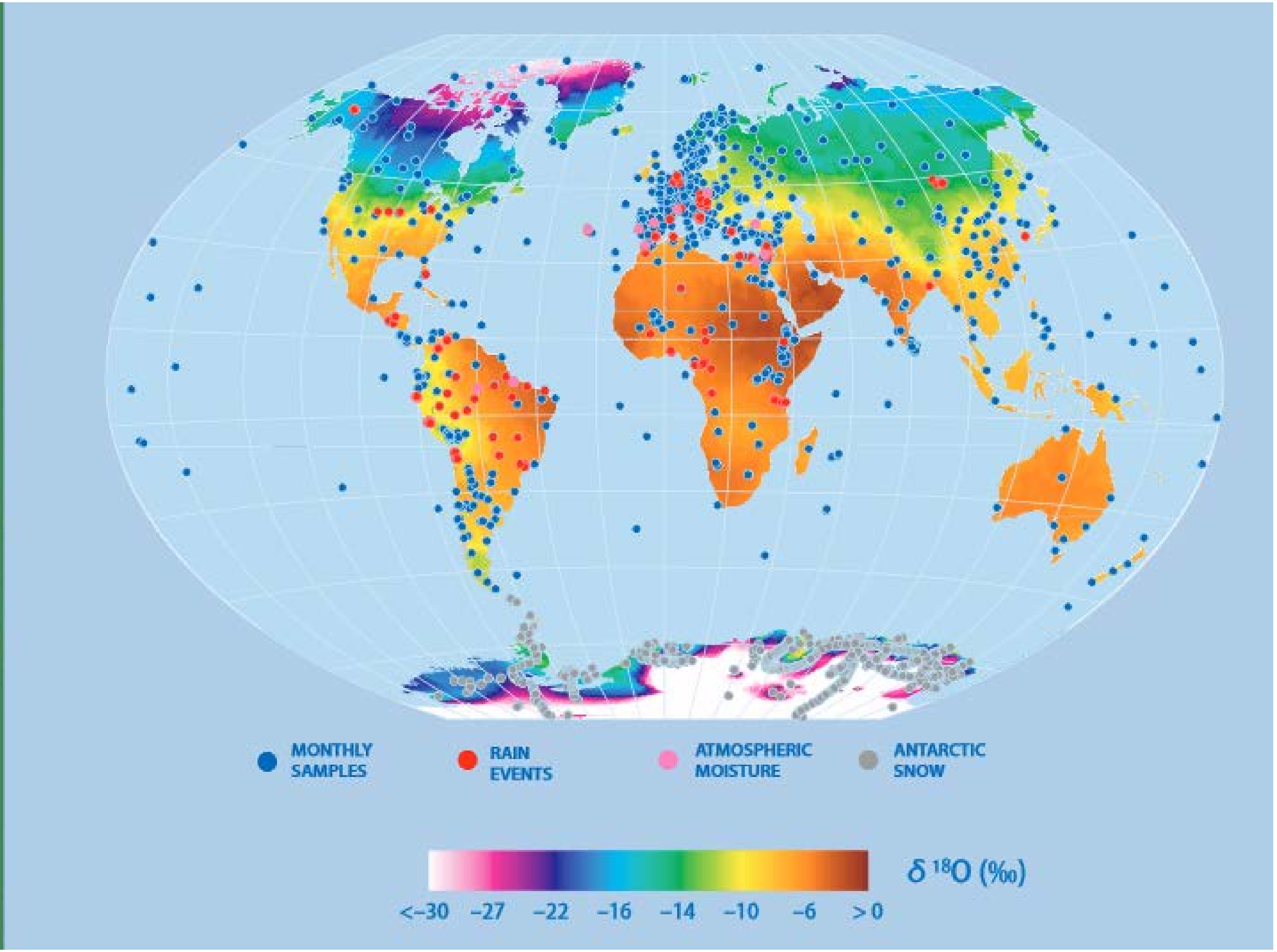
Global distribution of oxygen-18 (per mil, ‰) in precipitation produced by interpolation of long-term annual means from about 700 GNIP stations.

http://www-naweb.iaea.org/napc/ih/documents/other/GNIP%20brochure.pdf

www.iaea.org

IAEA GNIP Network

- **Valencia**
- **Armagh**



IAEA Helps Brazil Strengthen Isotope Monitoring of Precipitation

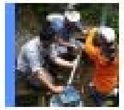
Aleksandra Peeva, IAEA Department of Nuclear Sciences and Applications

NOV
27
2018

The CPRM team after the set-up of the Recife Isotope monitoring station. This rainfall totalizer will be used to collect samples, whose isotopic signature will provide valuable additional data for the Global Network of Isotopes in Precipitation (GNIP). (Photo: R. Kirchheim/CPRM)

www.iaea.org

Related Stories



How Climate Change Affects Water Resources in Costa Rica

New Findings Unlock Climate Change Information Stored in Rain Samples

Related Resources

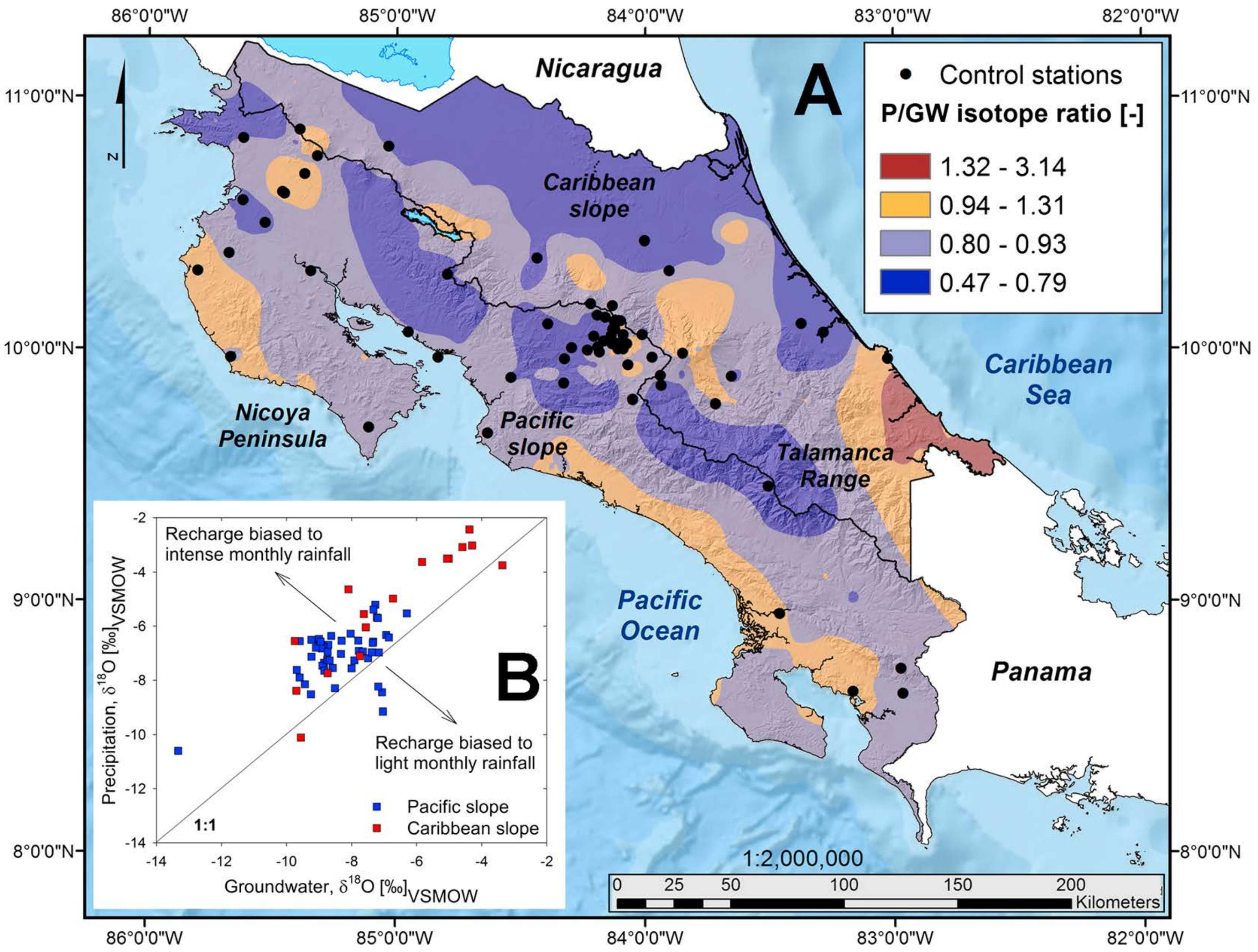
- Water
- Precipitation
- Climate Change: Making a Difference Through Nuclear Technologies, IAEA Bulletin (Vol. 56/2, June 2015)
- Global Network of Isotopes in Precipitation (GNIP)
- Isotope Hydrology Section

ISO-MECH

Interpreting changes in isotope ratios in precipitation allows scientists to determine changes in rainfall patterns and learn where, when and how groundwater is recharged. Rainfall patterns and their relationship with groundwater recharge is essential for understanding the impact of climate change on water availability (see Isotope hydrology).

ISO-MECH

- P/GW ratios
- Used to identify dominant groundwater recharge processes
- E.g. rapid recharge/ preferential flow versus slower soil matrix processes



Sanchez et al (2016, GRL)

ISO-MECH

- Groundwater isoscapes driven by precipitation – **shallow groundwater typically considered to represent annual precipitation**

- Shallow regional groundwater - indicator for long-term seasonally weighted precipitation inputs

- **Can hydrogeological factors also effect concentration?**

- Ground water systems can differ from mean annual precipitation due to seasonally biased recharge, infiltration evaporative processes, event-driven recharge, or by mixing with older ground water (Jasechko et al., 2014)

ISO-MECH

- Seasonal monitoring of $\delta^{18}O$ and δD variations from spatially distributed groundwater and rainfall stations across Ireland
- Aims: i) improve the understanding of precipitation origin, evaporative effects and estimated recharge rates, and ii) use results to conservatively trace bacterial (*E. coli*) ingress mechanisms
- Will improve knowledge of recharge mechanisms in the Irish subsurface environment and pilot a novel method for microbial source attribution and transport in the aquatic environment

Microbial Subsurface

Transport

Objectives

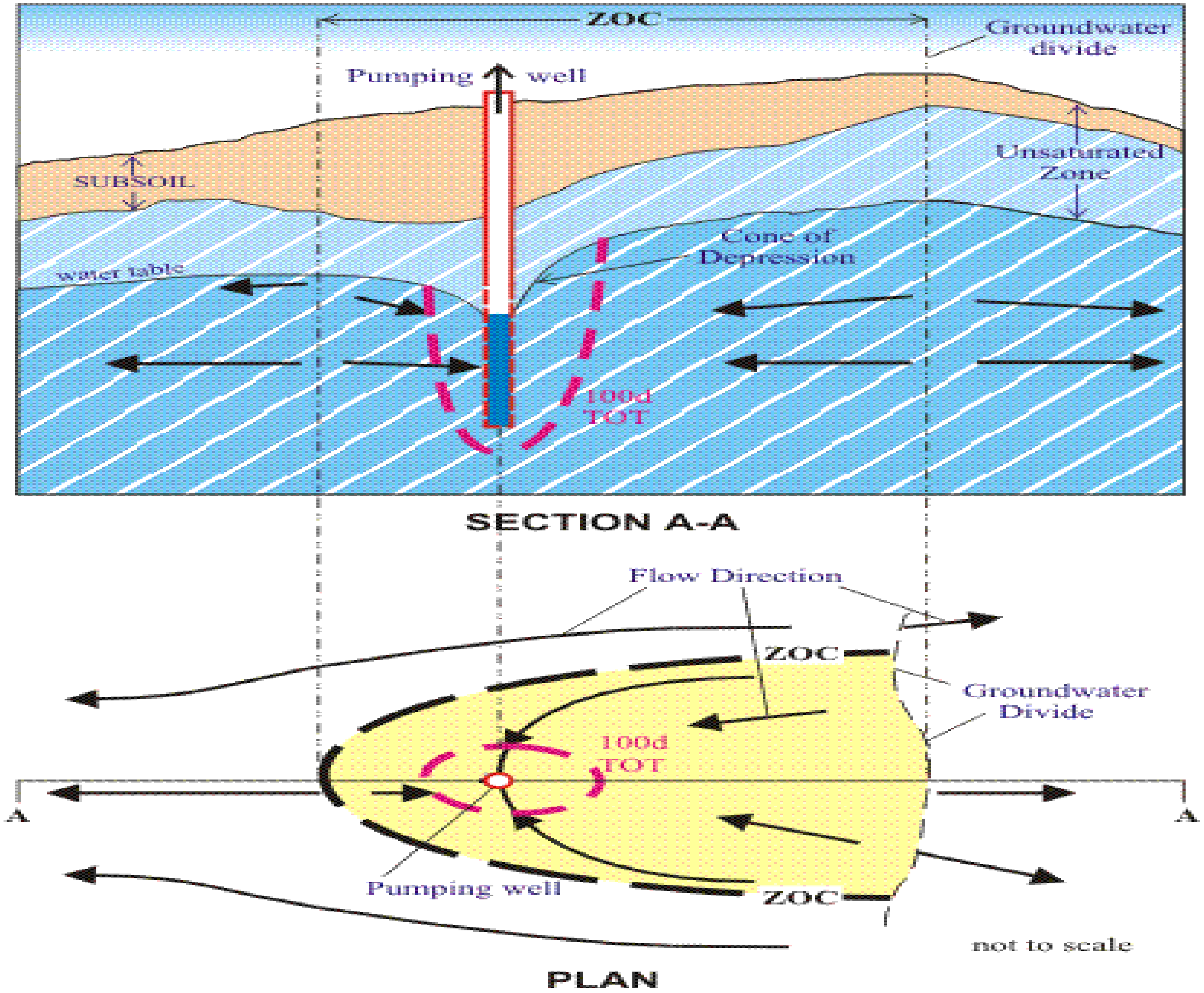
- Investigate the presence/absence of thermo-tolerant coliforms (>90% E. coli) with respect to all potential risk factors and develop multivariate "well susceptibility models for Republic of Ireland;
- Develop machine learning models for a very large integrated Ontarian dataset (940,000 groundwater samples);
- Infer subsurface microbial incidence and transport

Sampling . . . . . Lots and lots of sampling

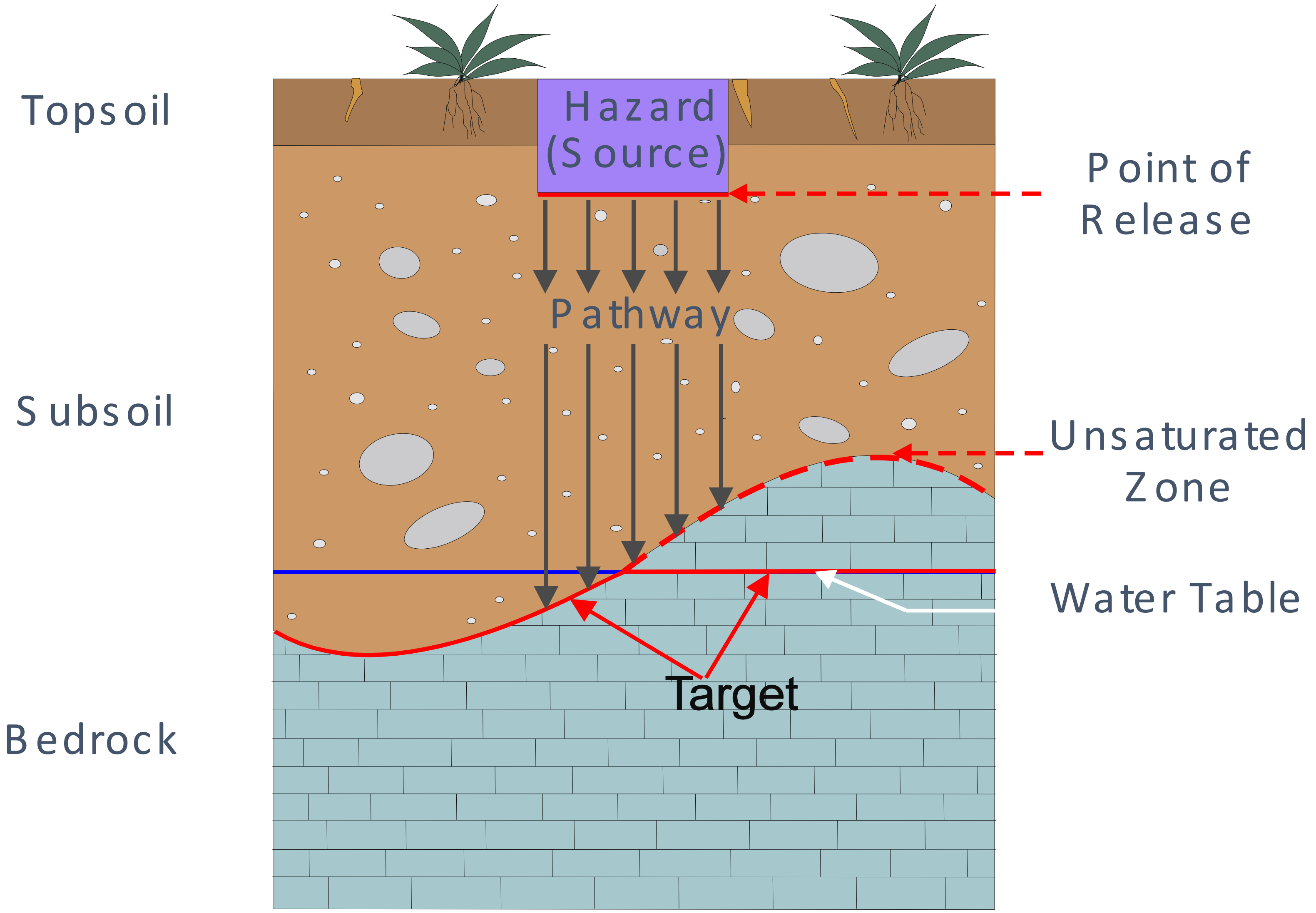




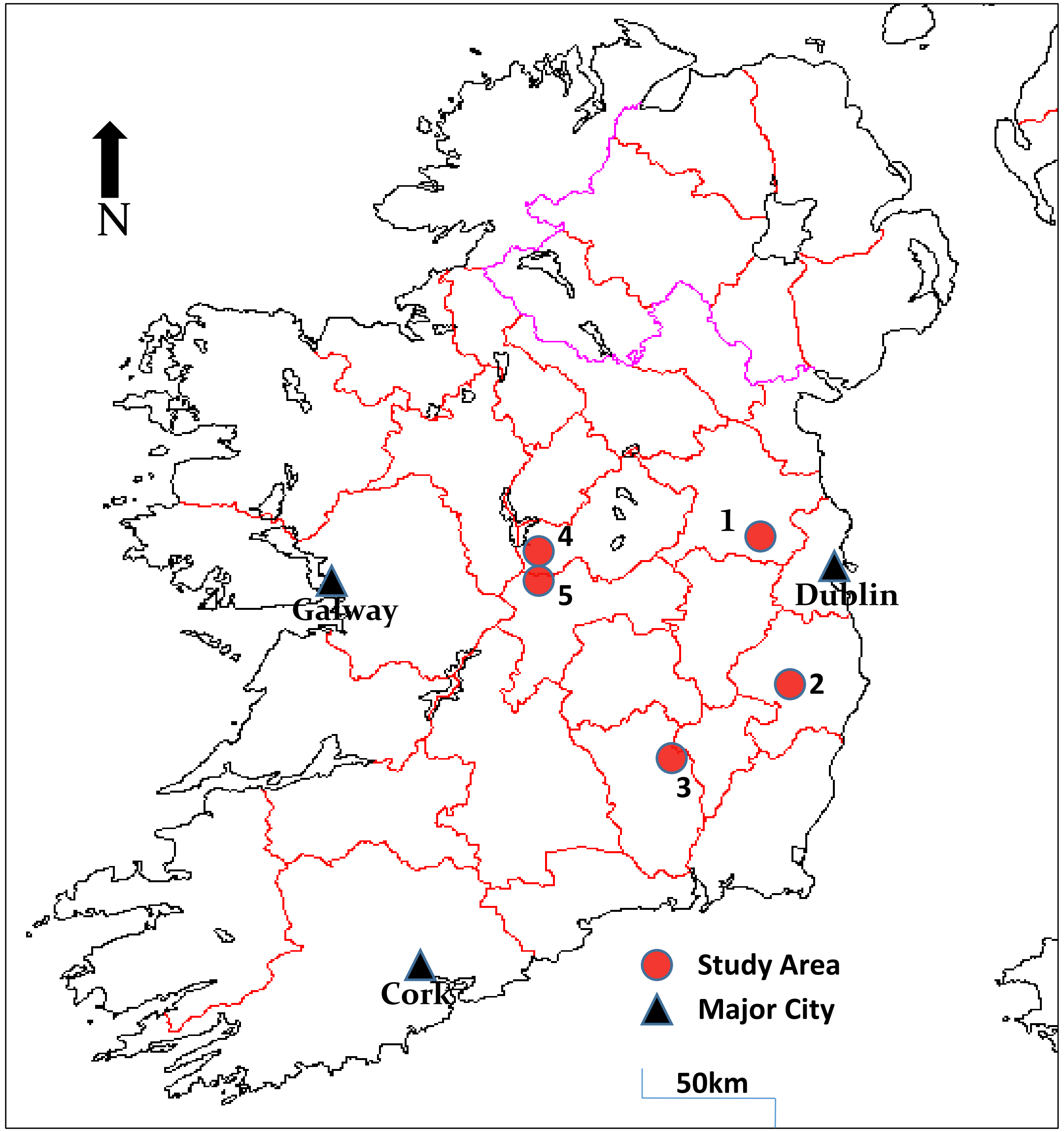
Contaminant Source Investigation



Aquifer vulnerability



Study Areas



Study Areas

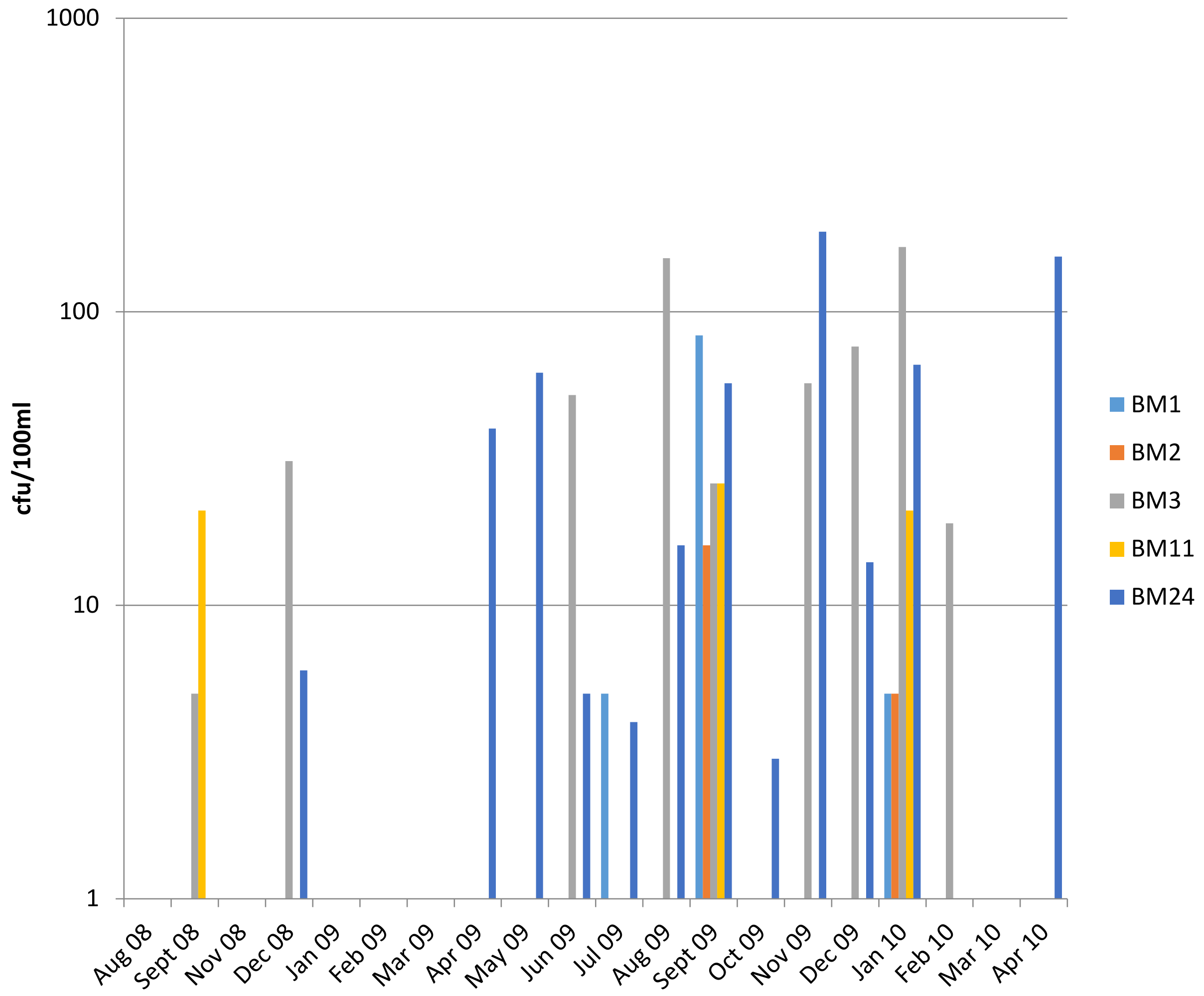
Study Area	Name	Bedrock	GW Vuln.	Aquifer Type
S.A. 1	Meath	Limestone	Low	Ll
S.A. 2	Wicklow	Granite	High	Ll/Pl
S.A. 3	Kilkenny	Sandstone Shale Limestone	Extreme	Pl
S.A. 4	Westmeath	Limestone	High	Ll
S.A. 5	Offaly	Limestone Sandstone	High	Ll/Lm

Risk Factor Analysis – Vulnerability

- E. coli presence variable among study areas
  - *High/Extreme* Vuln – 11% (SA3) to 44 % (SA5)
  - *Low* Vuln – 45% (SA1)

Lower than expected *E. coli* presence within *High/Extreme* vulnerability areas, while higher than expected within *Low* vulnerability area ($\chi^2 = 10.686$, $p = 0.03$)

Risk Factor Analysis - Precipitation



- 14/15 private wells positive for *E. coli* during monthly sampling
- Increased presence & magnitude during late summer & early winter
- 42.5% - *Low* Vuln
- 32% - *High*/Ex Vuln
- Correlation between 120h precip and *E. coli* (r = 0.785)

Hierarchical Logistic Regression

- 11 models in total
- Classification Cutoff point = 0.5
- Susceptibility models were developed to 90% predictive accuracy
- Will present Low and High Vuln. Models

	B	B Sig.	Model Sig.	H/L Sig.	R^2
Block 1:					
Septic Tank Setback Distance	-0.117	0.039			
Septic Tank Number <100m	-1.659	0.08			
Septic Tank Up-Grad	-15.174	0.04	0.035	0.349	0.204
Block 2:					
48-hour precipitation	-0.926	0.04			
120-hour precipitation	0.711	0.043			
30-day precipitation	-0.069	0.05	0.03	0.461	0.315
Block 3:					
Liner Clearance	-18.536	0.022			
Liner Cap Presence	-7.865	0.04	<0.001	0.817	0.759
Block 4:					
Agricultural Landuse	5.776	0.041			
Constant	48.812	0.027	<0.001	0.94	0.839

Hierarchies

Beta value

Variable significance within model

Hierarchy Significance

System Variability Explained

Low Vulnerability LR Model

- Significant hierarchies included:
  - Well Design Parameters – 52.8%
  - Septic Tank Proximity – 24.2%
  - Antecedent Precipitation – 13.2%
  - Agricultural Landuse – 9.5%

<u>Well Design Parameters</u> – Liner Clearance & Liner Cap

<u>Antecedent Precipitation</u> – 48-hour & 120-hour

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<u>Well Design Parameters</u> – Liner Clearance & Liner Cap

<u>Antecedent Precipitation</u> – 48-hour & 120-hour

WHAT'S MISSING?

HYDROGEOLOGY!

High/Extreme Vulnerability LR Model

- Significant hierarchies included:
  - Hydrogeological Setting – 33.1%
  - Well Design Parameters – 29.8%
  - Septic Tank Proximity – 22.1%
  - Antecedent Precipitation – 13%

Well Design Parameters – Liner Clearance ; Wellhead Cover; 10m Wellhead Radius Condition

Antecedent Precipitation – 30-day

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Antecedent Precipitation – 30-day

Vulnerability Model Comparison

Low Vulnerability

- Local hydrogeology not found to be significant
- Well design highly significant (52.8%)
- Septic tank proximity significant (24.2%)
- Short-term precipitation significant (13.2%)
- Agriculture significant (9.5%)

High/Extreme Vulnerability

- Local hydrogeology significant (33.1%)
- Well design significant (29.8%)
- Septic tank proximity significant (22.1%)
- Medium-term precipitation significant (13%)
- Agriculture not found to be significant

Vulnerability – Recharge – Runoff – Precipitation - Susceptibility

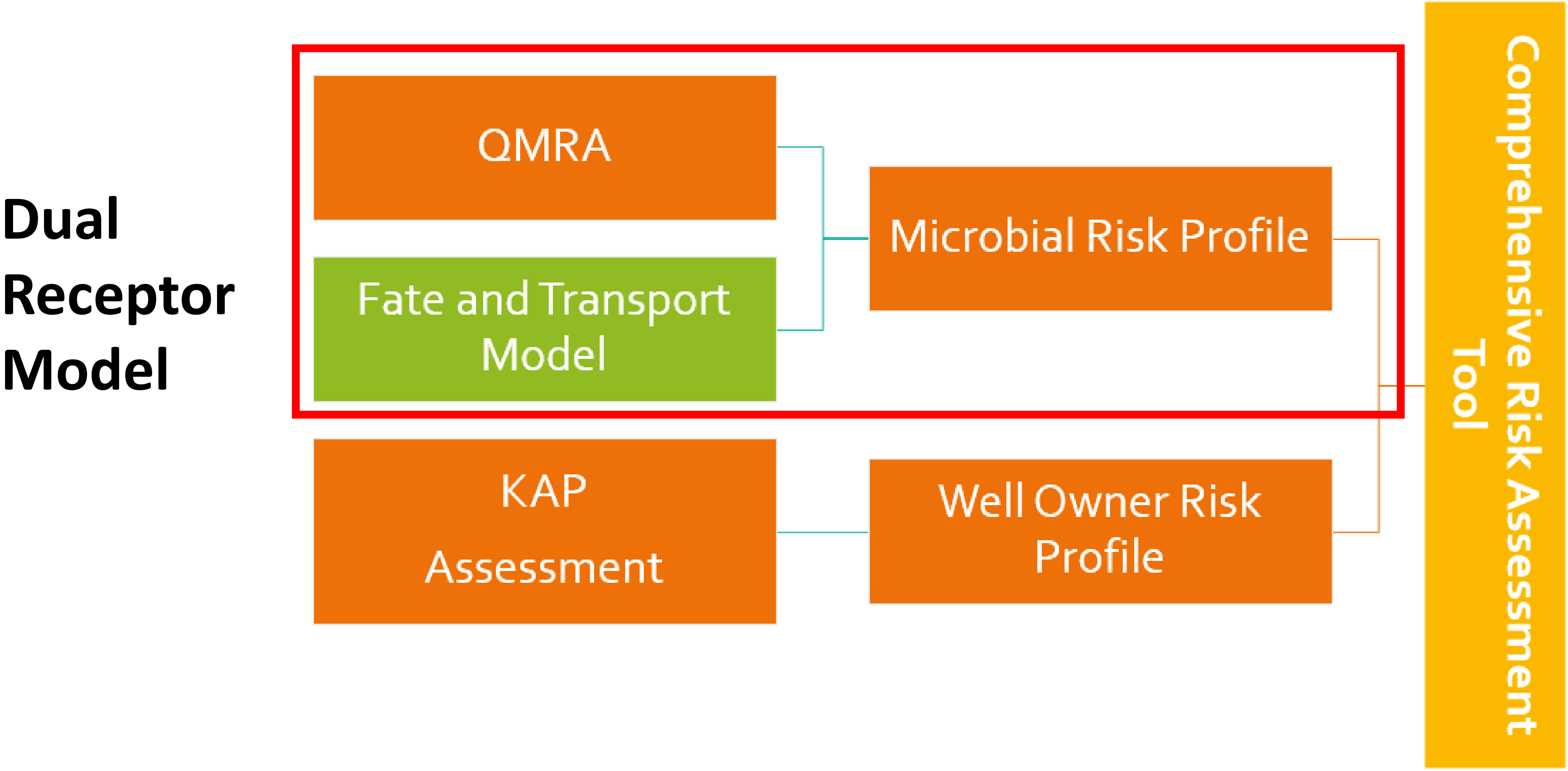
The link between subsoil permeability, recharge, runoff and vulnerability

Subsoil		Recharge	Runoff	Aquifer vulnerability
Permeability	Thickness			
High	1–3 m	High	Low	Extreme
	>3 m	High	Low	High
Moderate	1–3 m	High	Low	Extreme
	3–10 m	Intermediate	Intermediate	High
	>10 m	Intermediate	Intermediate	Moderate
Low	1–3 m	Intermediate	Intermediate	Extreme
	3–5 m	Low	High	High
	5–10 m	Low	High	Moderate
	>10 m	Low	High	Low

Source: Misstear *et al*.; Hydrogeology Journal (2009) 17: 275-285

The “Ontario Dataset”

The "WELLness" Project



Water Well
Information System

Well Testing
Information System

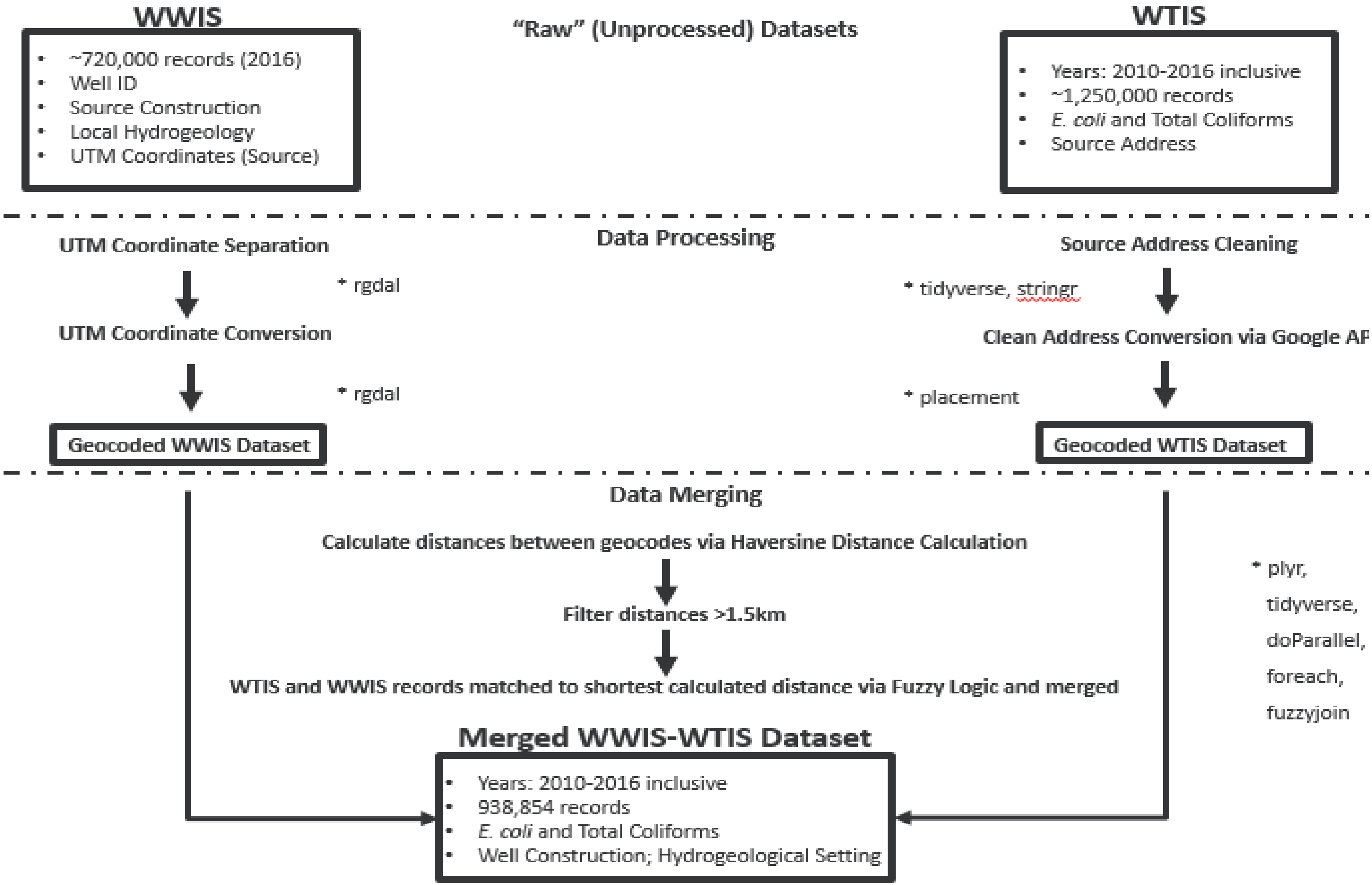
WWIS

- ~720,000 records (2016)
- Well ID
- Source Construction
- Local Hydrogeology
- UTM Coordinates (Source)

"Raw" (Unprocessed) Datasets

WTIS

- Years: 2010-2016 inclusive
- ~1,250,000 records
- *E. coli* and Total Coliforms
- Source Address


WWIS
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Source Construction
Local Hydrogeology
UTM Coordinates (Source)
"Raw" (Unprocessed) Datasets
WTIS
Years: 2010-2016 inclusive
~1,250,000 records
E. coli and Total Coliforms
Source Address
Data Processing
UTM Coordinate Separation
* rgdal
UTM Coordinate Conversion
* rgdal
Geocoded WWIS Dataset
Source Address Cleaning
* tidyverse, stringr
Clean Address Conversion via Google AP
* placement
Geocoded WTIS Dataset
Data Merging
Calculate distances between geocodes via Haversine Distance Calculation
Filter distances >1.5km
WTIS and WWIS records matched to shortest calculated distance via Fuzzy Logic and merged
* plyr,
tidyverse,
doParallel,
foreach,
fuzzyjoin
Merged WWIS-WTIS Dataset
Years: 2010-2016 inclusive
938,854 records
E. coli and Total Coliforms
Well Construction; Hydrogeological Setting

WTIS

- Years: 2010-2016 inclusive
- ~1,250,000 records
- *E. coli* and Total Coliforms
- Source Address

Untidy Source Addresses

↓

Cleaned Addresses

↓

Geocode Cleaned Addresses with Google's API

↓

WTIS Dataset with Clean, Geocoded Addresses

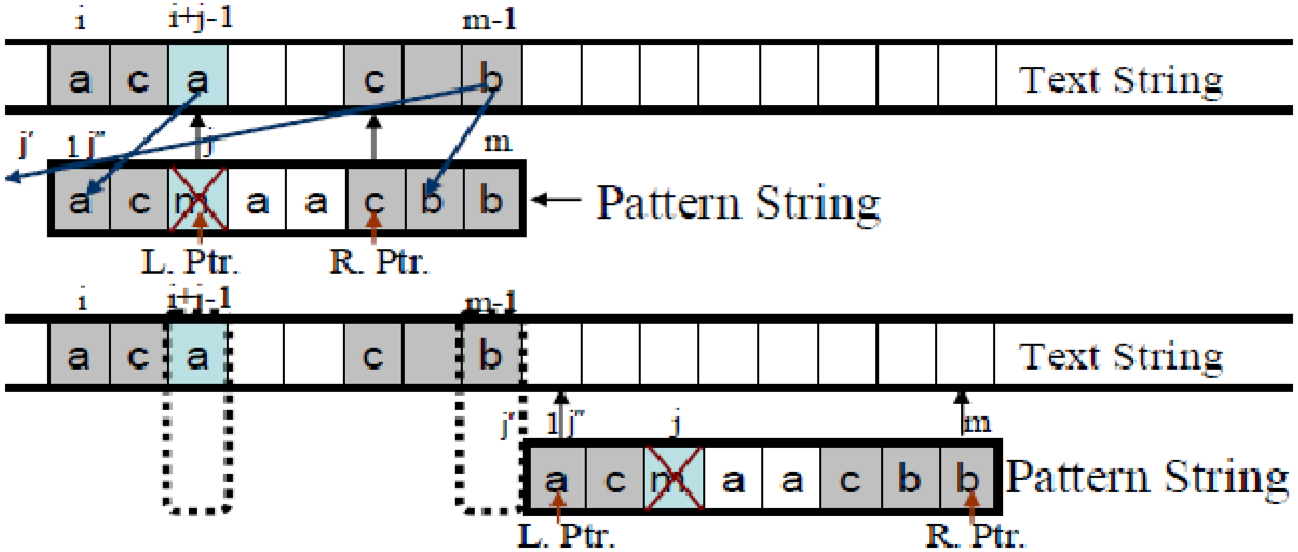
↓

```
gdalinfo ~/openev/utm.tif
Driver: GTiff/GeoTIFF
Size is 512, 512
Coordinate System is:
PROJCS["NAD27 / UTM zone 11N",
    GEOGCS["NAD27",
        DATUM["North_American_Datum_1927",
            SPHEROID["Clarke 1866",6378206.4,294.978698213901]],
        PRIMEM["Greenwich",0],
        UNIT["degree",0.0174532925199433]],
    PROJECTION["Transverse_Mercator"],
    PARAMETER["latitude_of_origin",0],
    PARAMETER["central_meridian",-117],
    PARAMETER["scale_factor",0.9996],
    PARAMETER["false_easting",500000],
    PARAMETER["false_northing",0],
    UNIT["metre",1]]
Origin = (440720.000000,3751320.000000)
Pixel Size = (60.000000,-60.000000)
Corner Coordinates:
Upper Left  (  440720.000, 3751320.000) (117d38'28.21"W, 33d54'8.47"N)
Lower Left  (  440720.000, 3720600.000) (117d38'20.79"W, 33d37'31.04"N)
Upper Right (  471440.000, 3751320.000) (117d18'32.07"W, 33d54'13.08"N)
Lower Right (  471440.000, 3720600.000) (117d18'28.50"W, 33d37'35.61"N)
Center      (  456080.000, 3735960.000) (117d28'27.39"W, 33d45'52.46"N)
Band 1 Block=512x16 Type=Byte, ColorInterp=Gray
```

<u>tidyverse/stringr</u>

Whitespace Tools

Patterns Matching Functions

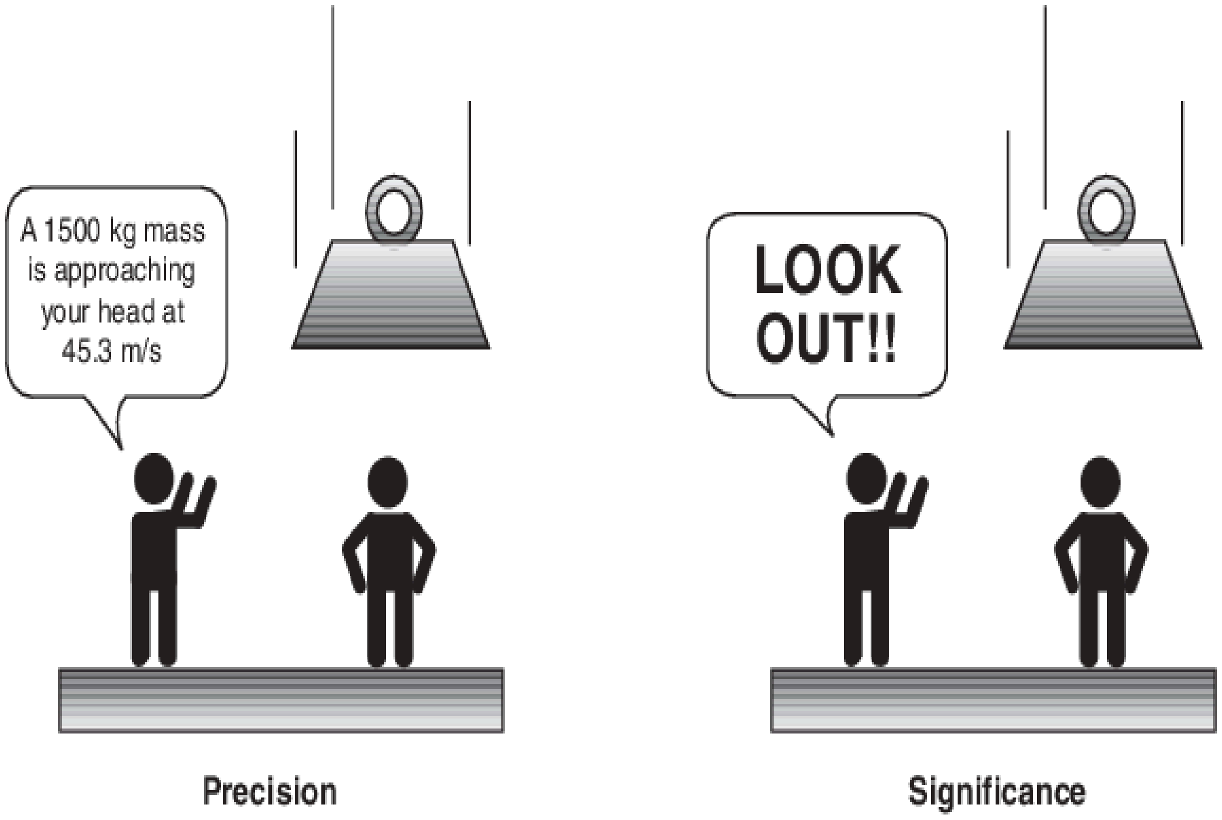


Fuzzy Logic Joining/Merging

Join tables together based not on whether columns match exactly, but whether they are similar by some comparison. Implementations include string (Calculated Haversine) distance and regular expression matching (Address; BR Geology)

WELL ID	POSTAL CODE
1500474 ()	K4M1A5
1500474 ()	K4M1H2
1500474 ()	K4M1C1

WELL ID	POSTAL CODE
1501665 ()	K1V1E9
1501665 ()	K1V1.00E+09
1501667 ()	K1V1E9
1501667 ()	K1V1.00E+09

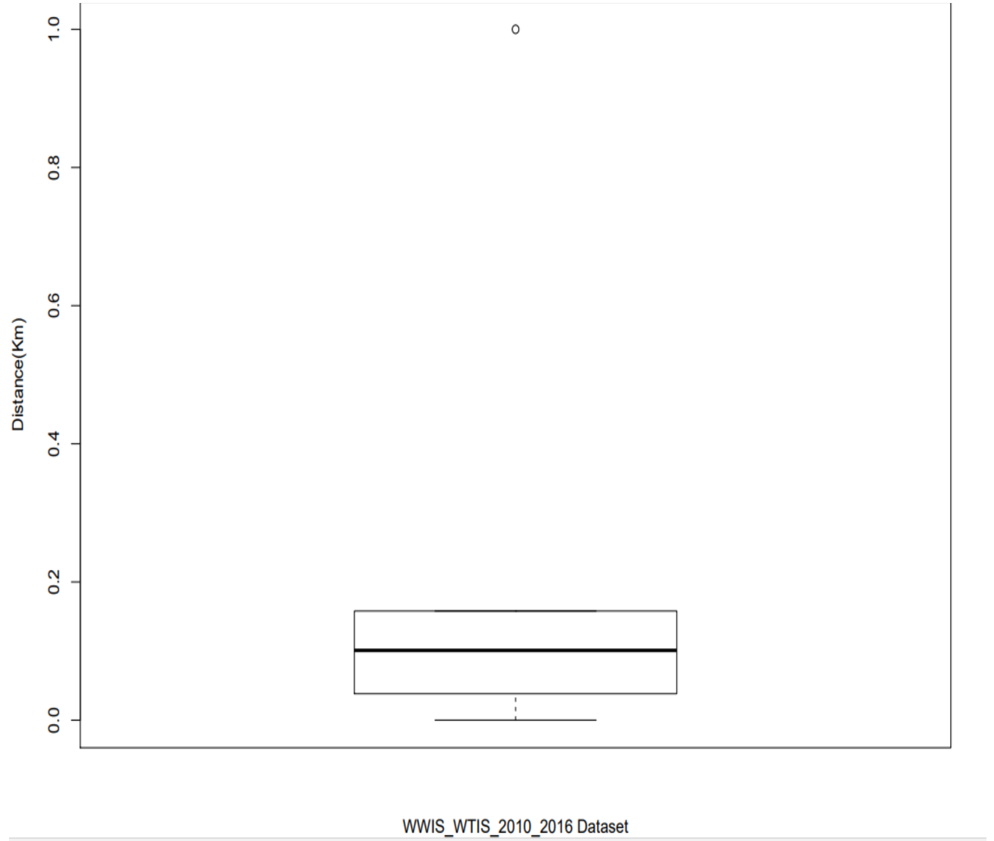


Boolean Logic

Fuzzy Logic

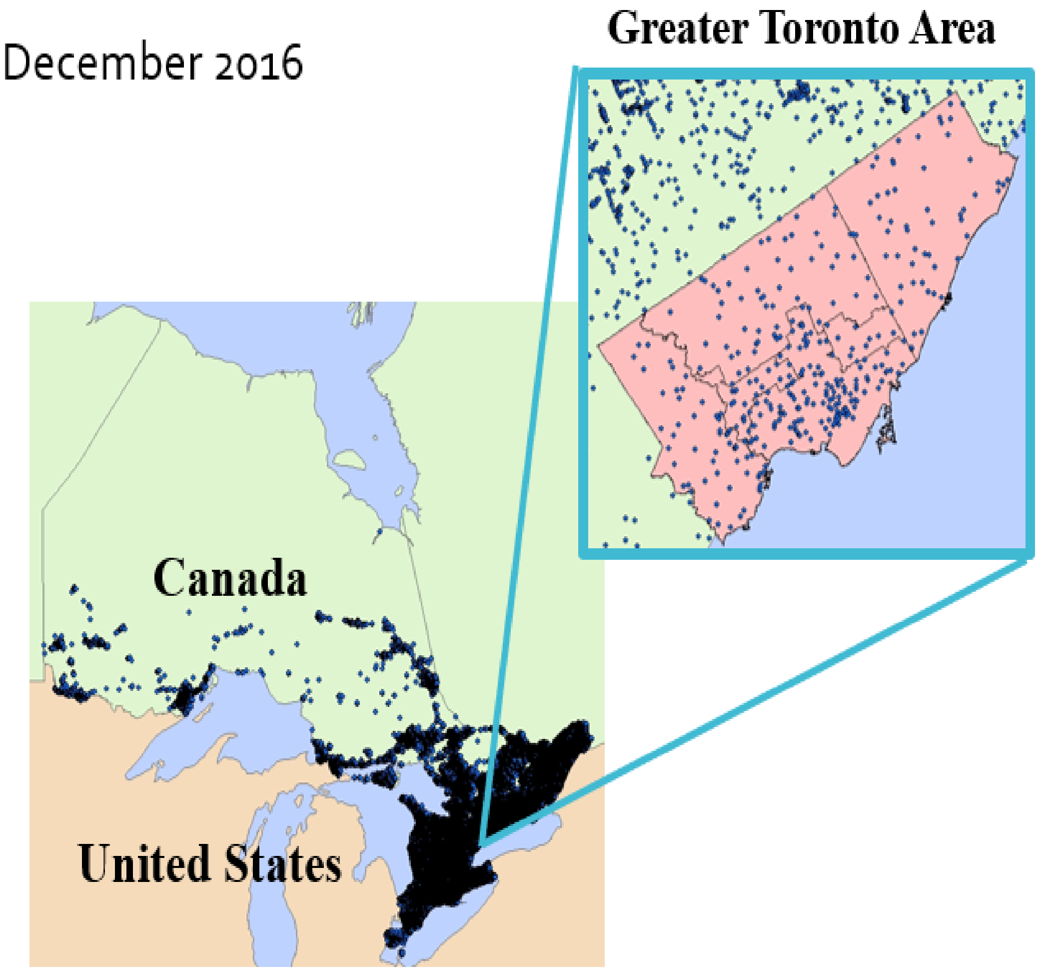
Distance Analysis of Merged Dataset

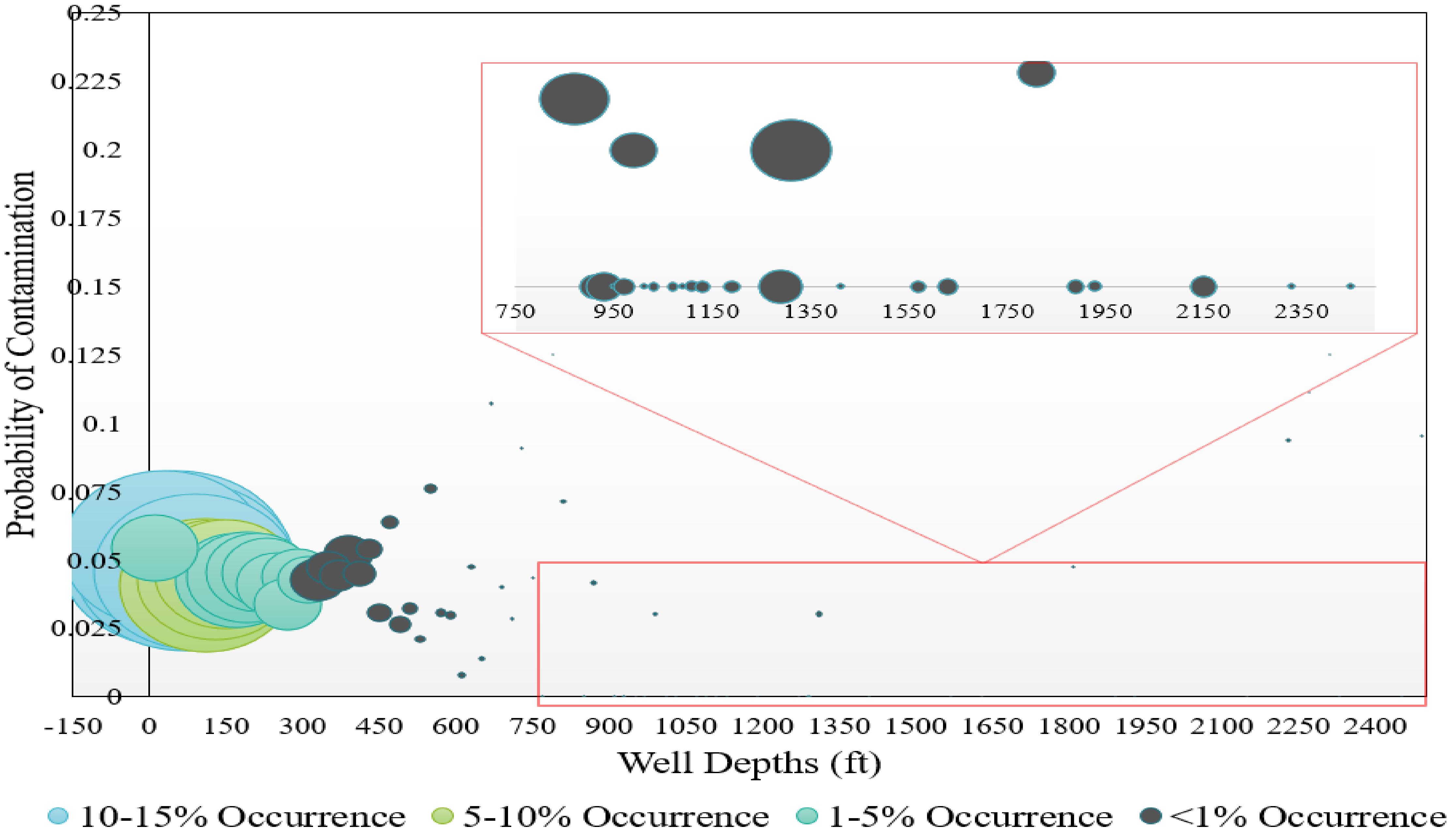
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
6.078e-05	0.0383	0.07531	0.1266	0.158	1



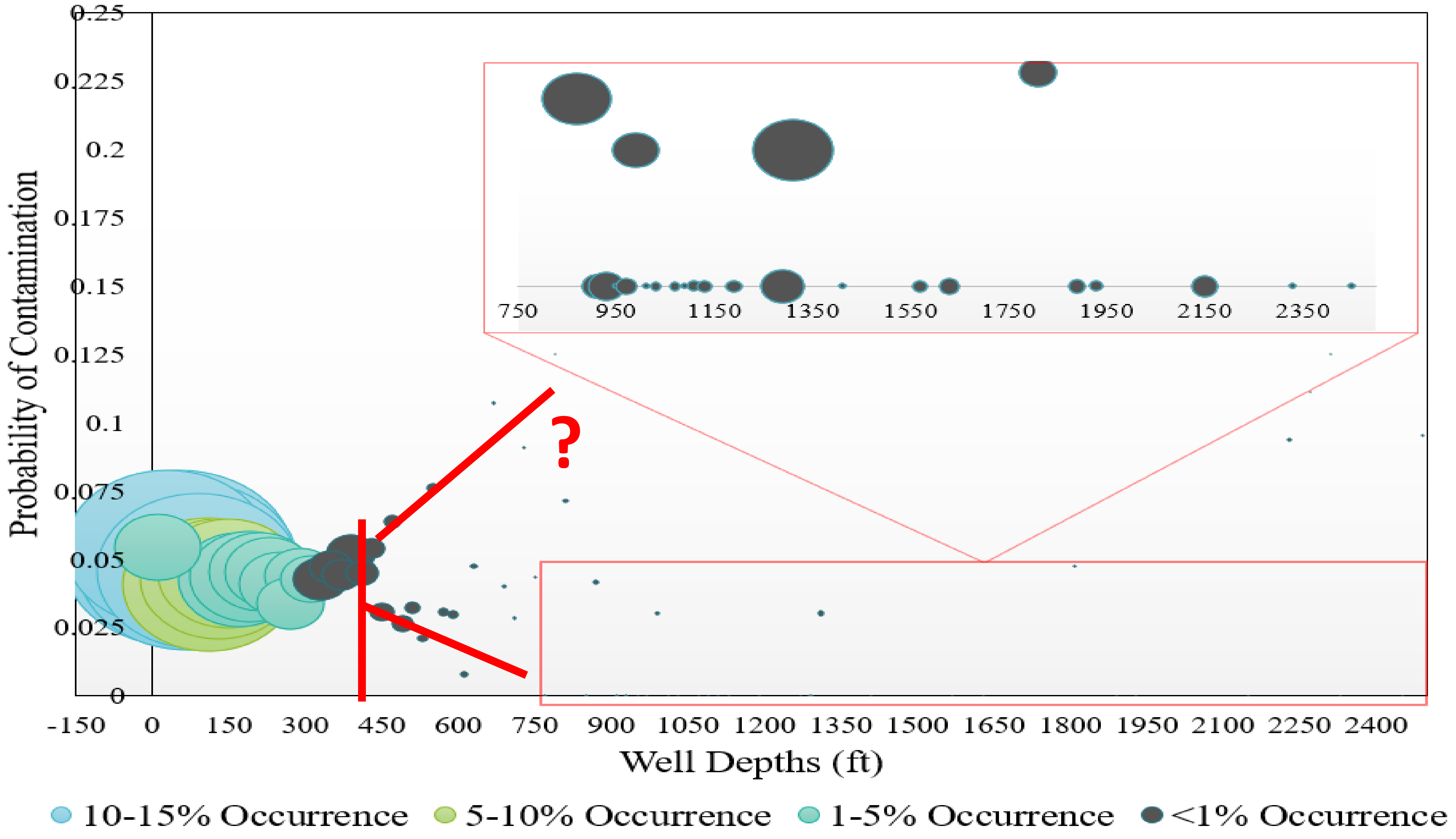
Approximately 62,000,000 datapoints!!!

- 938 854 testing records from 159 531 unique wells
  - 1-404 observations/well (averaging 11 observations/well)
- January 2010 – December 2016

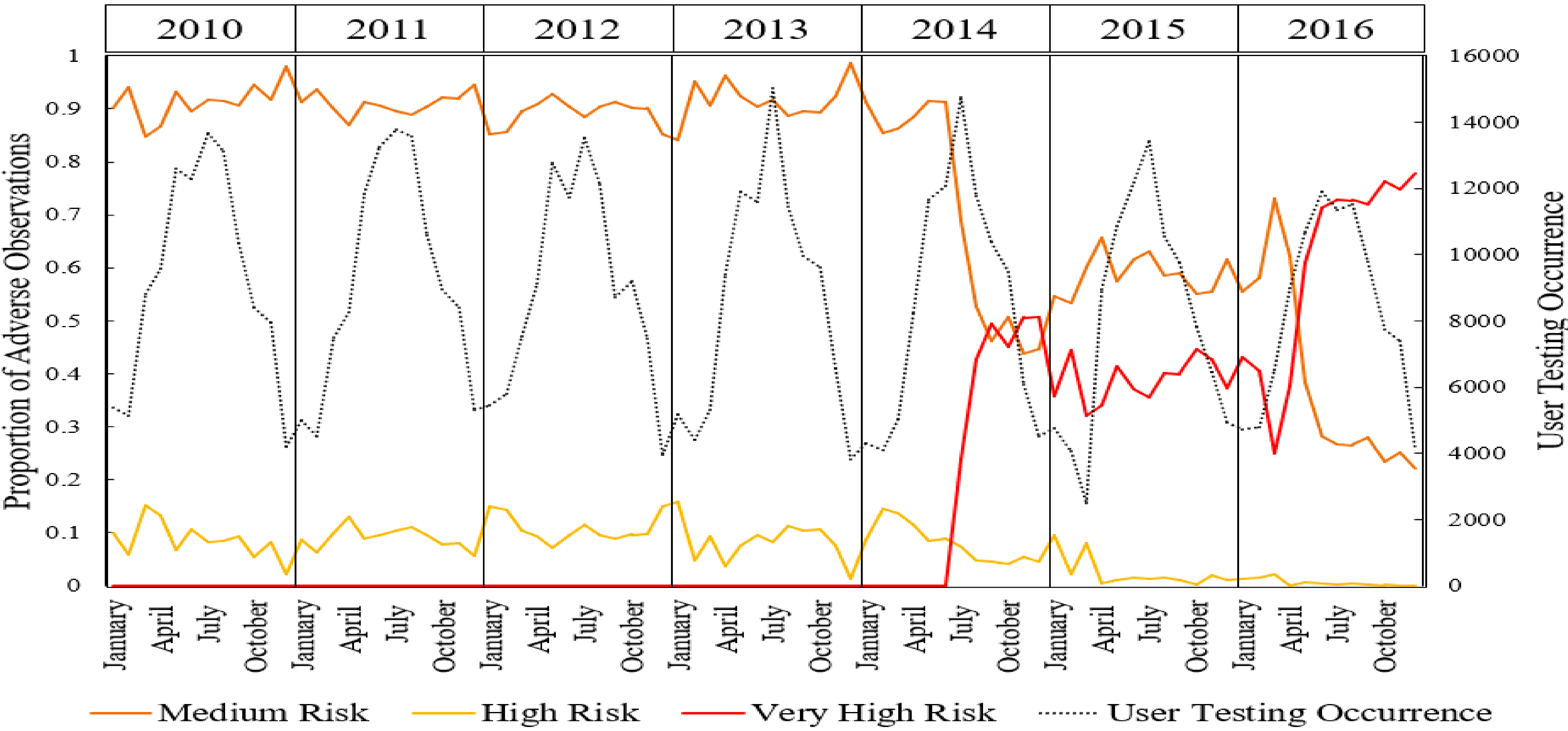




Probability of Contamination
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
-150
0
150
300
450
600
750
900
1050
1200
1350
1500
1650
1800
1950
2100
2250
2400
Well Depths (ft)
750
950
1150
1350
1550
1750
1950
2150
2350
10-15% Occurrence
5-10% Occurrence
1-5% Occurrence
<1% Occurrence



Probability of Contamination
0.25
0.225
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0
-150 0 150 300 450 600 750 900 1050 1200 1350 1500 1650 1800 1950 2100 2250 2400
Well Depths (ft)
750 950 1150 1350 1550 1750 1950 2150 2350
?
10-15% Occurrence
5-10% Occurrence
1-5% Occurrence
<1% Occurrence



2010
2011
2012
2013
2014
2015
2016
Proportion of Adverse Observations
User Testing Occurrence
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2000
4000
6000
8000
10000
12000
14000
16000
January
April
July
October
Medium Risk
High Risk
Very High Risk
User Testing Occurrence

Conclusions

- Developed models seem to work logically as predictive tools;

- Private well susceptibility is a product of a number of factors including; well type, well design and construction, hazard source proximity, geological setting (*High/Extreme* vuln), precipitation and aquifer vulnerability;

- Significance of short-term precipitation (*Low* vuln) suggests rapid by-pass contamination mechanisms and very specific point/zone of ingress;

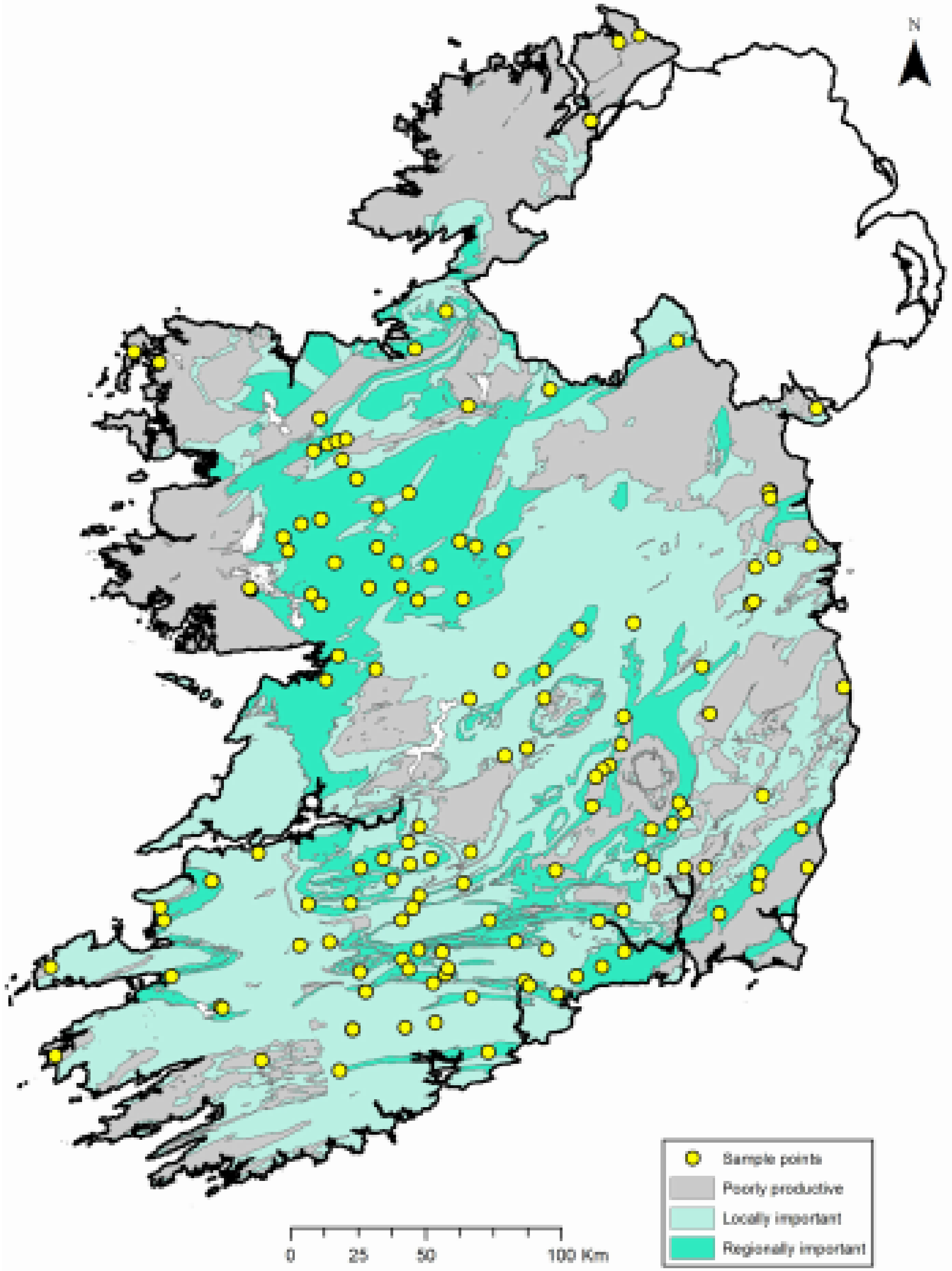
Conclusions

- Significance of medium-term antecedent precipitation (High Vuln) suggests slower contamination pathways;
- Significance of hydrogeo setting within High Vuln cohort and source characteristics within total cohort suggests multiple mechanisms;
- Vulnerability/susceptibility/risk probability are extremely fluid concepts and depend on multiple variables and variable interactions
- Contamination mechanisms (well and aquifer) are as unique as the well or aquifer they are associated with.

O^{18} isoscape for Ireland and geospatial drivers

O^{18} Isoscape study

- Uplands – Pre Cambrian to Lower Palaeozoic igneous, metamorphic and sedimentary rocks
- West and Midlands – Carboniferous rocks (karstified)
- Groundwater – generally unconfined
- Aquifer classification – based on productivity, potential yield and extent



O^{18} Isoscape drivers

- Variation of ~ 3‰ (Min 7.5 ‰, Max 4.1‰)
- Progressive depletion to eastern coast
- Primary determinants?

➢ Location with respect to orographically influenced rainfall

➢ Annual precipitation volume

➢ Dominance by winter recharge

Modern groundwater recharge

Table 2
Univariate association analyses between measured groundwater $\delta^{18}O$ and continuous (scale) variables; Non-parametric Spearman R_{sp}. Two-tailed tests of significance with cases excluded on pair-wise basis.

	N	R_{sp}	p
Location:			
X-Coordinate	142	−0.438	<0.001
Y-Coordinate	142	−0.408	<0.001
Elevation (m)	142	−0.052	0.540
Recharge:			
Recharge Coefficient (mm/year)	141	0.153	0.053
Recharge Capacity (mm)	141	0.046	0.590
Estimated Recharge (mm)	141	0.167	0.048
Seasonal Climate:			
Mean Annual Precipitation	142	0.530	<0.001
Spring Mean Precipitation	142	0.483	<0.001
Summer Mean Precipitation	142	0.425	<0.001
Autumn Mean Precipitation	142	0.561	<0.001
Winter Mean Precipitation	142	0.519	<0.001
Mean Annual Temperature	142	0.414	<0.001
Spring Mean Temperature	142	0.372	<0.001
Summer Mean Temperature	142	0.156	0.063
Autumn Mean Temperature	142	0.449	<0.001
Winter Mean Temperature	142	0.536	<0.001
Antecedent Precipitation			
24-h	142	0.110	0.223
48-h	142	0.171	0.019
120-h	142	−0.033	0.617
10-day	142	−0.078	0.321
30-day	142	0.265	0.002
60-day	142	0.211	0.011
90-day	142	0.349	<0.001
120-day	142	0.470	<0.001
150-day	142	0.250	0.001

Note: Spring – March, April, May; Summer – June, July, August; Autumn – September, October, November; Winter – December, January, February.

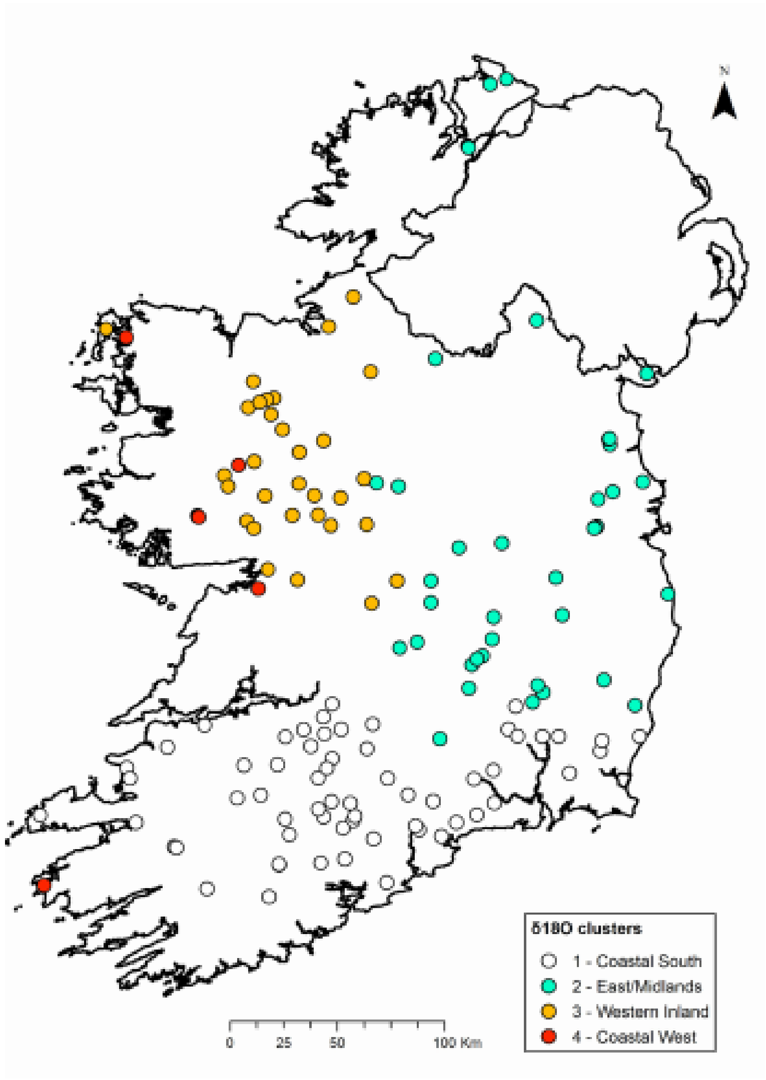
O^{18} Isoscape drivers

- Logit modelling of locational clusters
- Local/regional (hydro)geological setting exerts a secondary influence on $\delta^{18}O$ composition

Table 4
Multinomial Logit model for developed groundwater $\delta^{18}O$ clusters.

Effect	−2 Log Likelihood of Reduced Model	Chi-Square*	df	Sig.
Model Intercept	196.861	0.000	0	
AnnRainfall*AnnTemp	270.960	74.099	3	<0.001
Sample Source	217.526	20.664	3	<0.001
Gen_Aquifer_Type	214.097	17.236	6	0.008
Drainage (Dry/Not Dry)	205.847	8.986	3	0.029

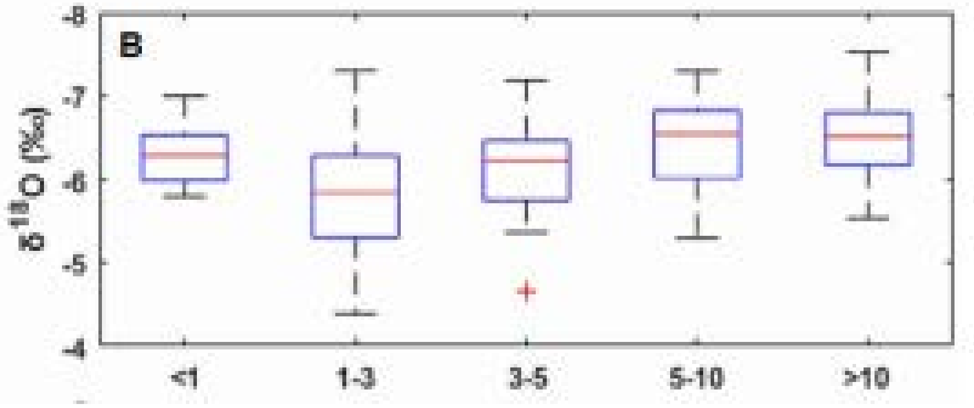
* The chi-square statistic is the difference in −2 log-likelihoods between the final model and a reduced model. The reduced model is formed by omitting an effect (variable) from the final model.

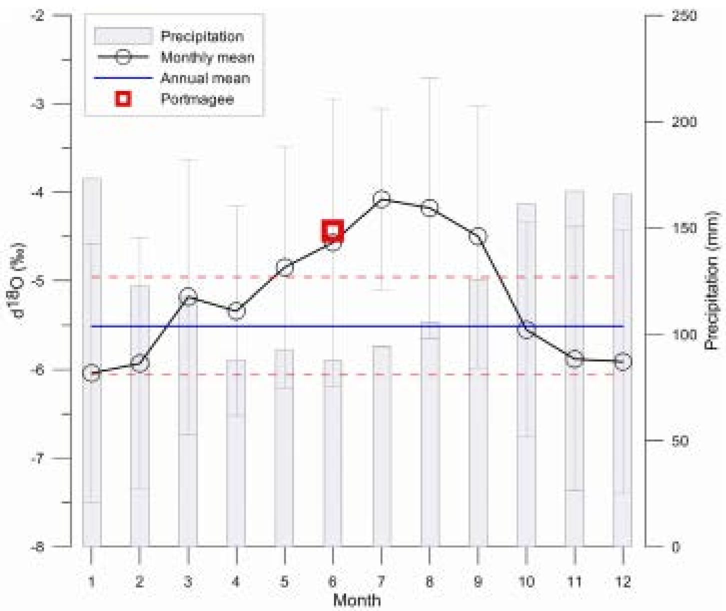


O^{18} Isoscape drivers

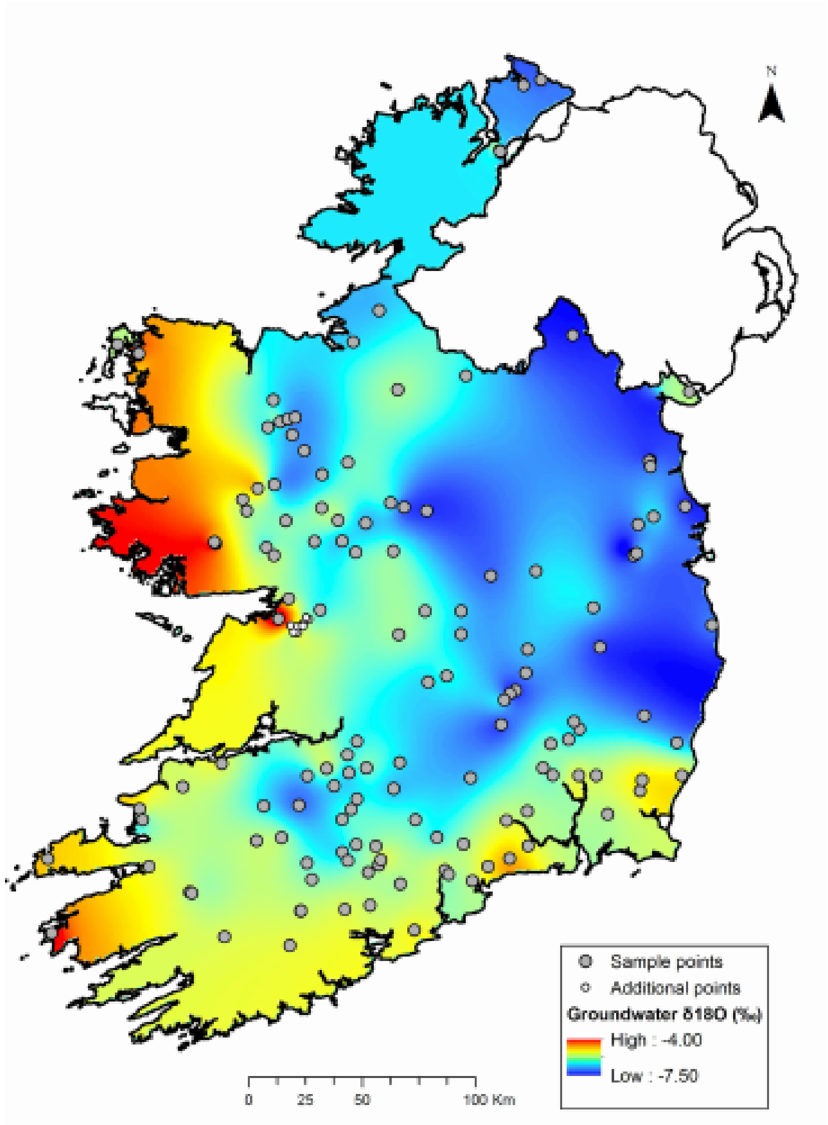
- High productivity bedrocks (e.g. karst limestone), bedrock aquifers with little or no soil/subsoil cover, and regions characterised by High/Extreme groundwater vulnerability, found to be more likely to attenuate the seasonal precipitation $\delta^{18}O$ composition.

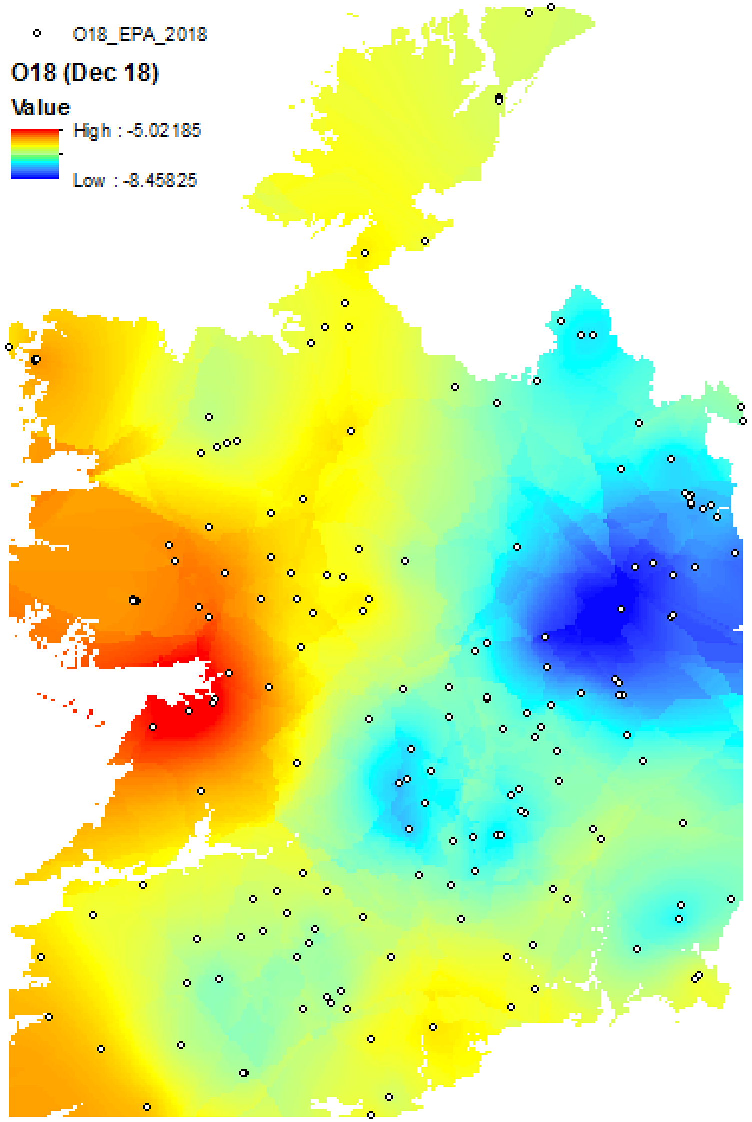
- Groundwater from poorly productive bedrocks, regions with high groundwater residence times (e.g. bedrocks capped with significant subsoil depths), and Low/Moderate aquifer vulnerability areas, were more likely to reflect the long–term mean annual precipitation $\delta^{18}O$ composition.





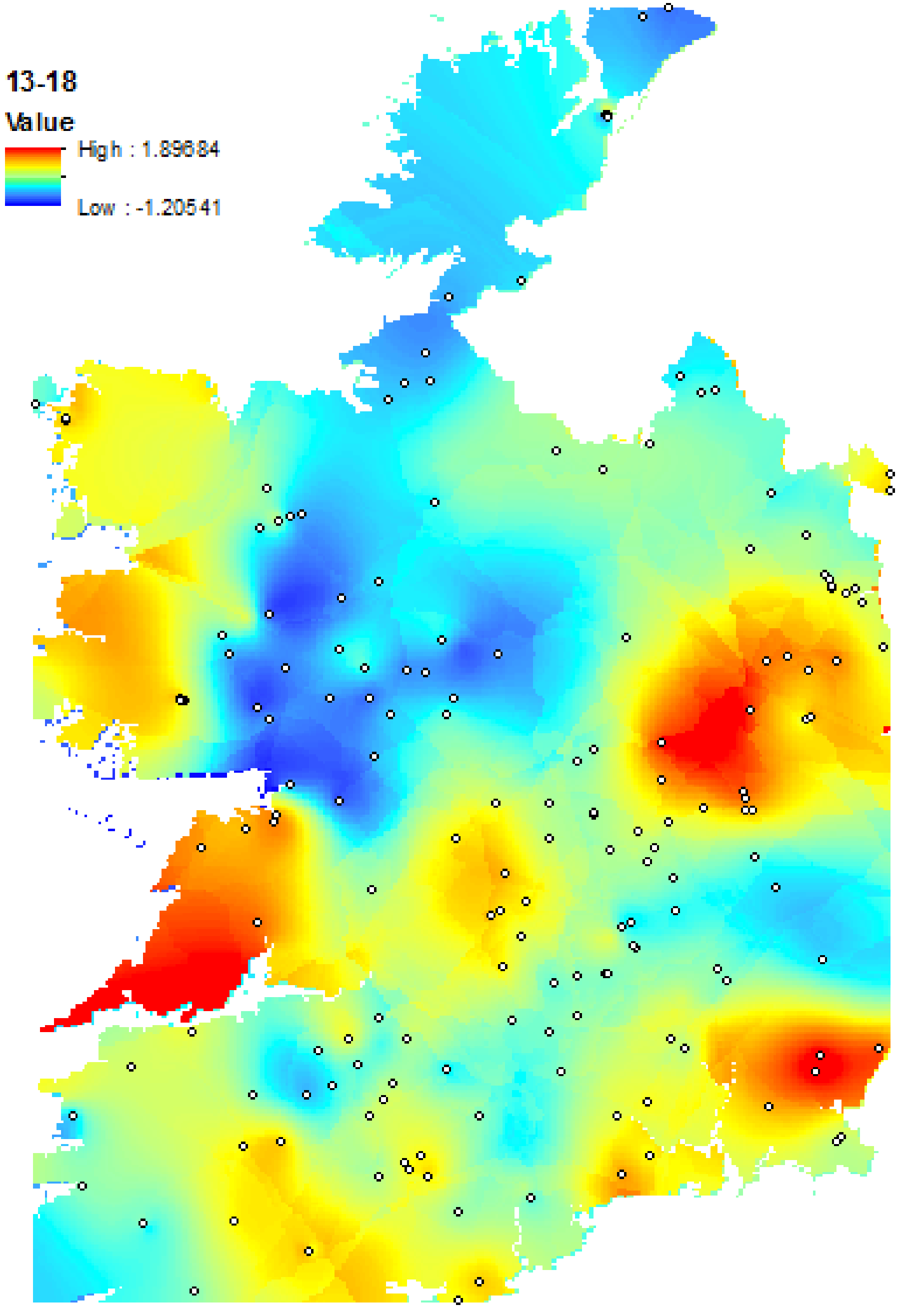
2018 'Drought'



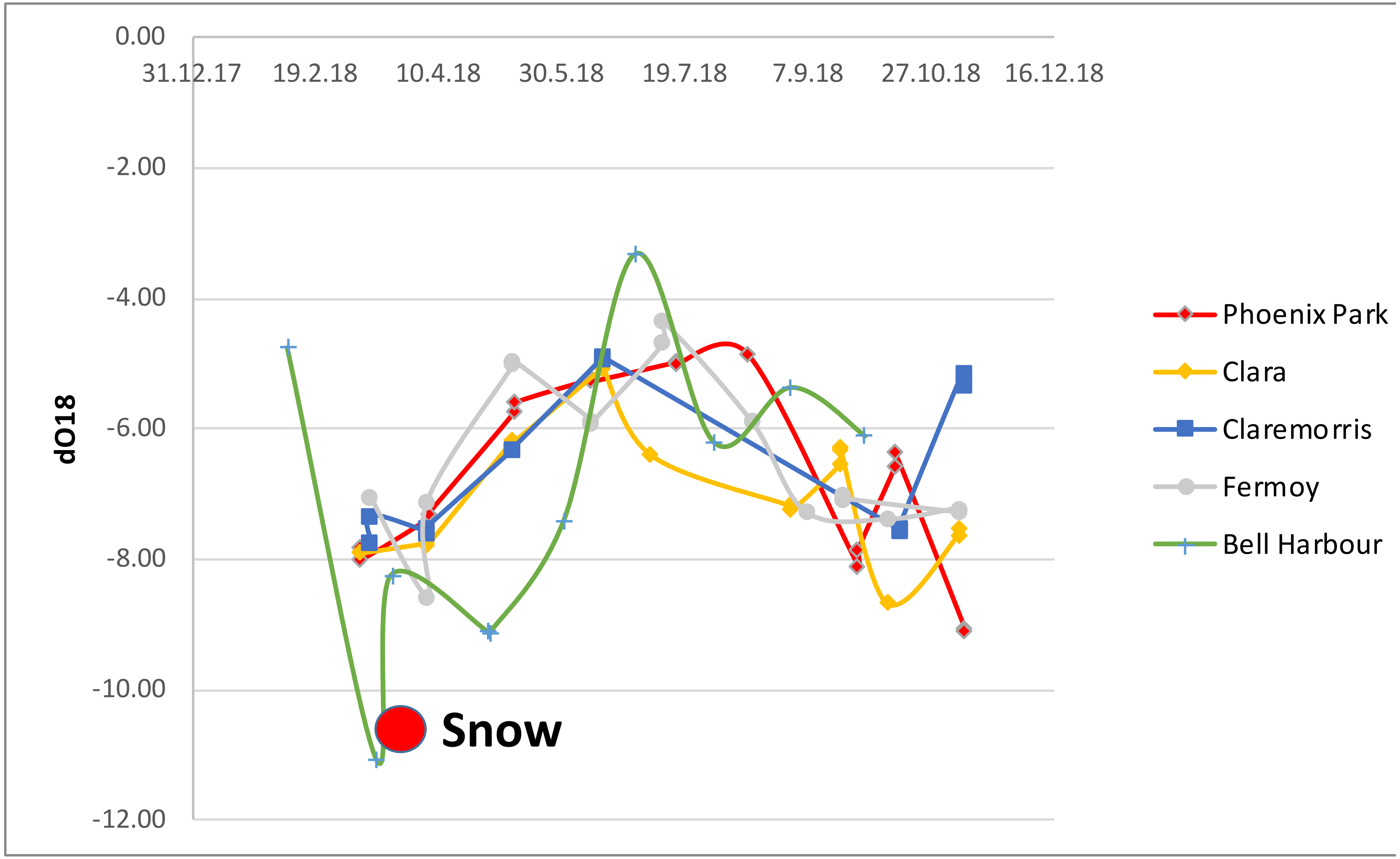


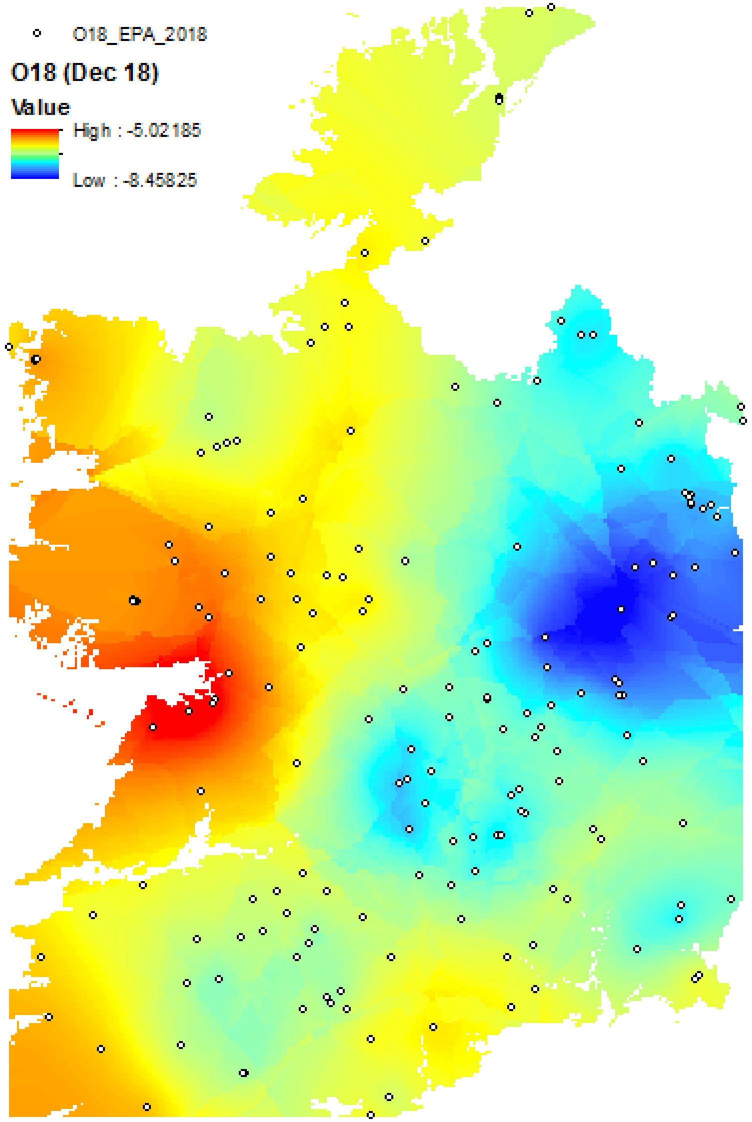
2018 ‘Drought’

- Increase ~ 1 mil in karst area (e.g. from -6.3 to -5.6) – Karst aquifers
- Decrease in east ~ 1 mil in karst area (e.g. from - 6.6 to -7.9) – Ll aquifers
- Faster recharge to west? GW-SW interaction in karst systems
- East – more representative of annual rainfall concentration



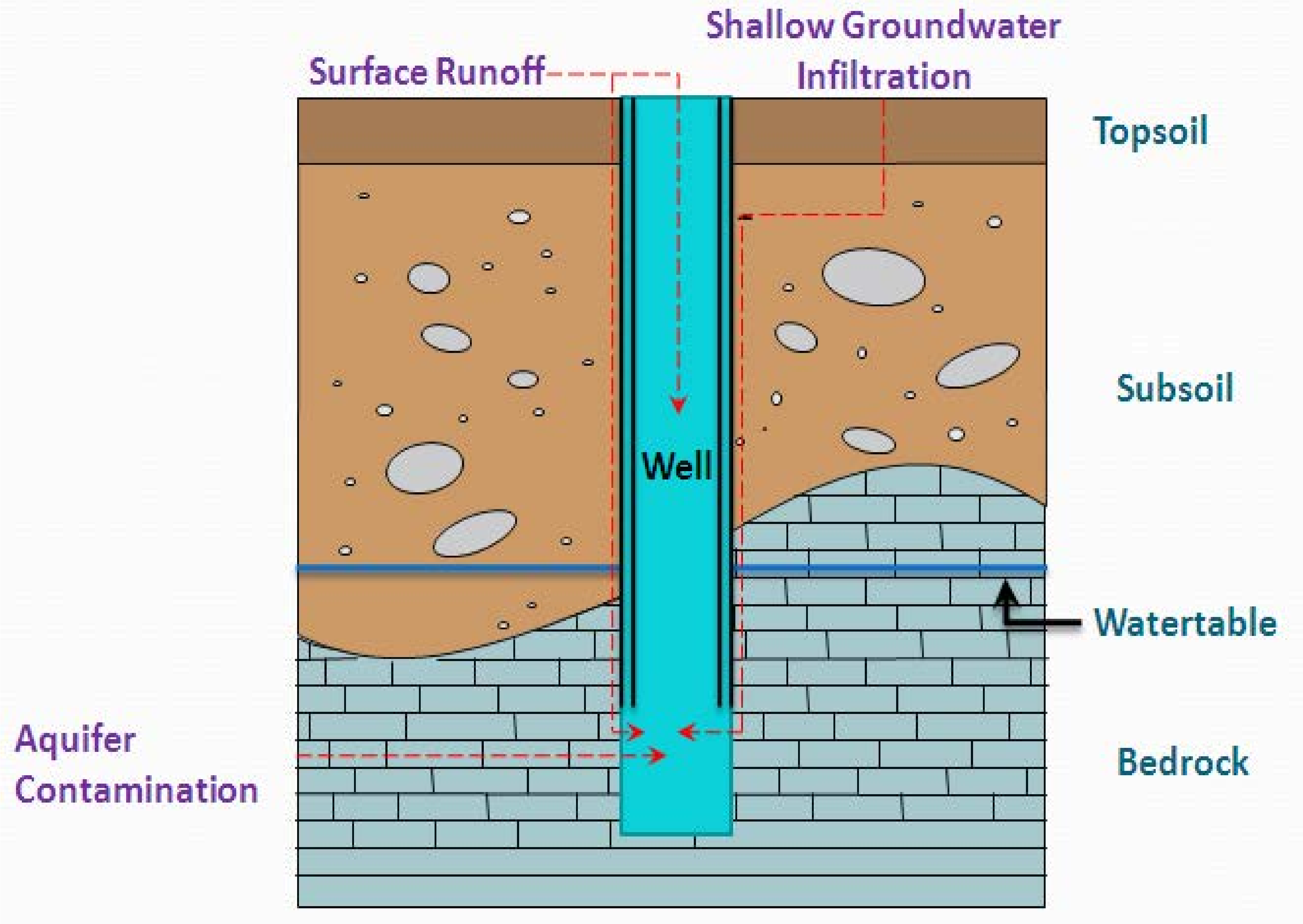
Precipitation dynamic





Enteric Microbes and Isotopes - Mechanistic Inference

Contamination Mechanisms



Mechanism affects:

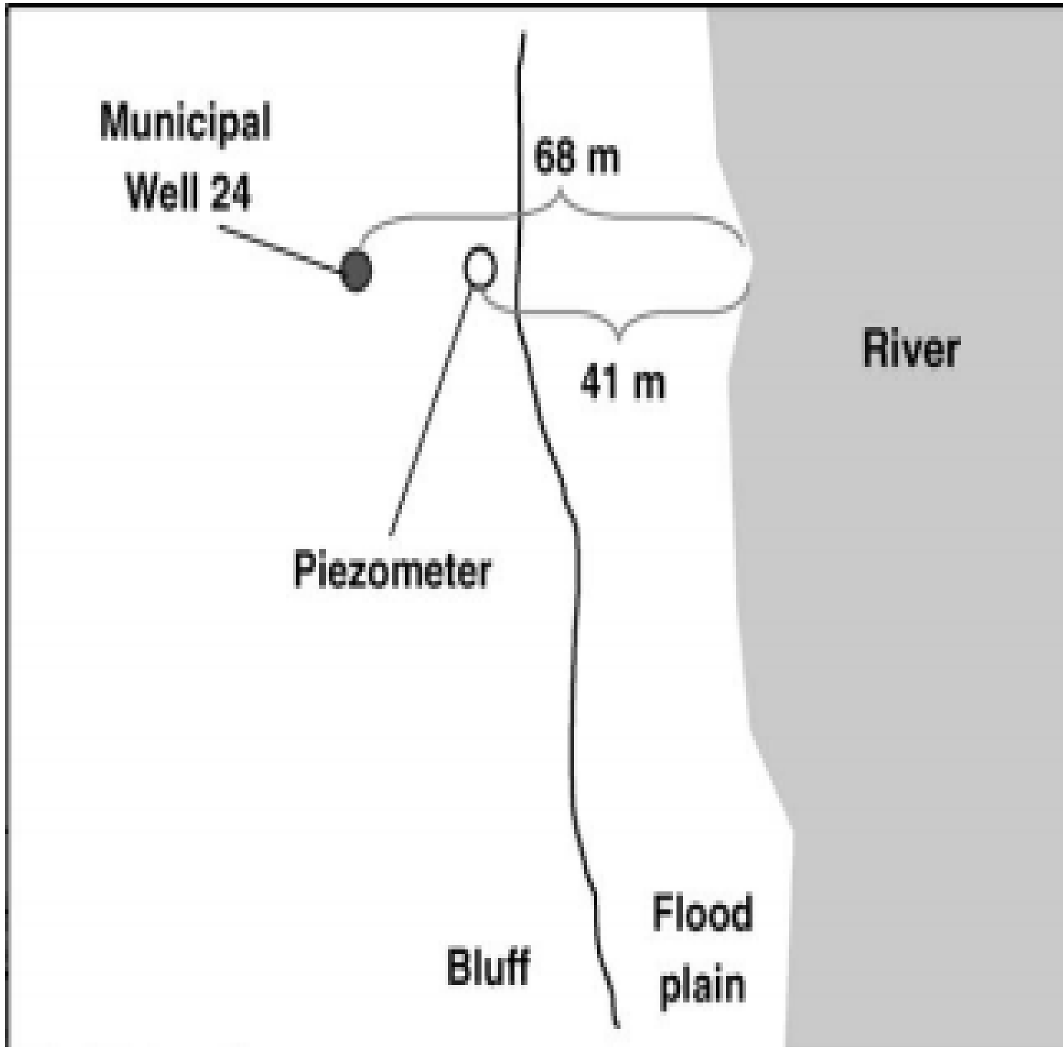
- Incidence
- Frequency
- Seasonality
- Concentration
- Predictive Accuracy
- Likelihood of Infection
- Acquired Immunity
- Ability to design interventions

Microbes and Isotopes – The Theory

- Surface water (and “new” groundwater) can be a source of contamination in a drinking water well, an understanding of the volume of surface water and travel time to the well is needed to assess a well’s vulnerability/susceptibility/risk prob,
- Seasonal, spatio-temporally distinct isotopic signals could be used as an indicator,
- Stable Isotopes are DEFINITELY not suitable as a tracker/tracer, but may shed light on source- or aquifer-specific mechanisms

Hunt et al., 2005; Journal of Hydrology

- Stable isotope ratios of oxygen in river water at the City of La Crosse, Wisconsin; peak to peak seasonal variation over 2 years,
- 13 urban (public) wells sampled over same period,
- 12-month time-series from 1 well and piezometer located between river,
- Time of travel (TOT) of floodwater assessed using 4 methods; GW Temp, Virus culture, Particle tracking (Model), and Age Dating (3H–3 He)
- NB: No precipitation isotopes



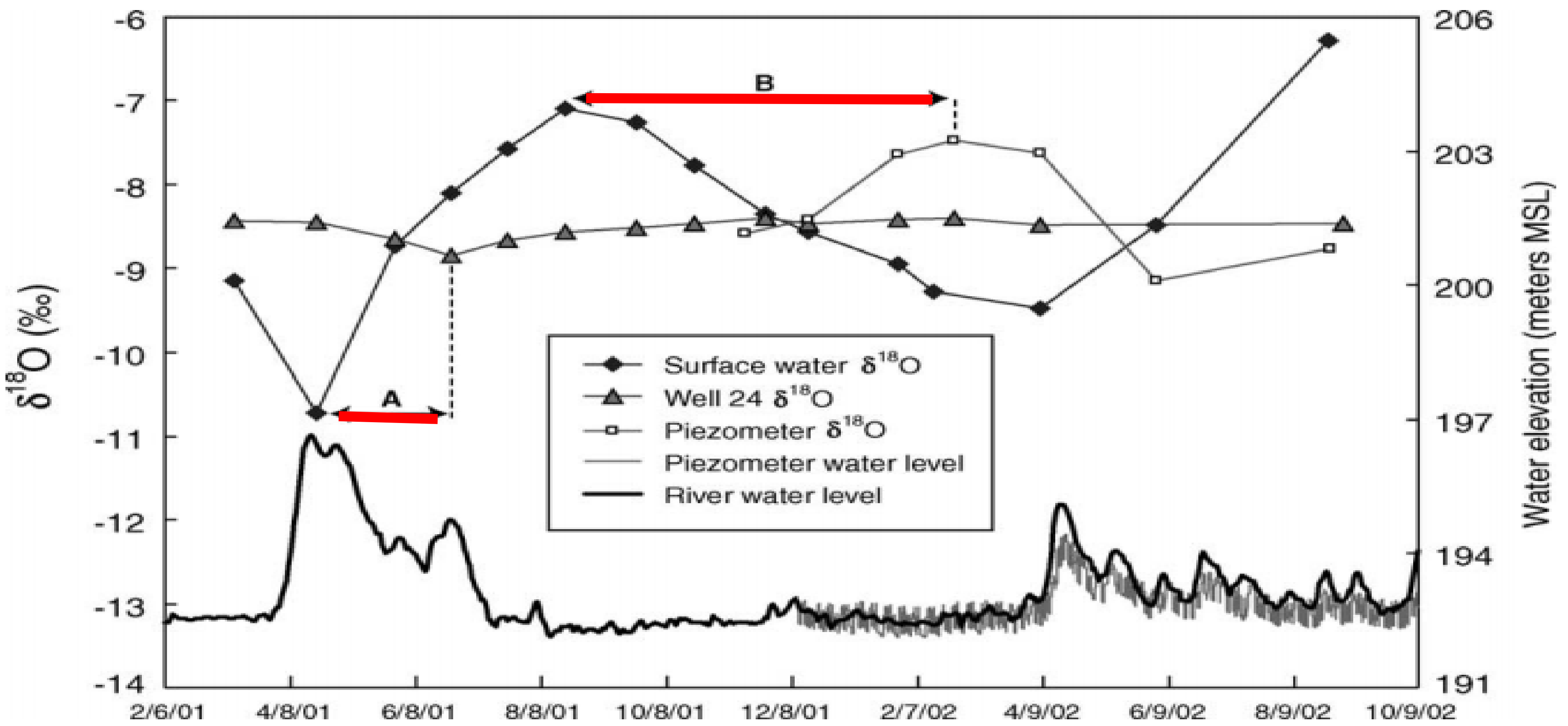
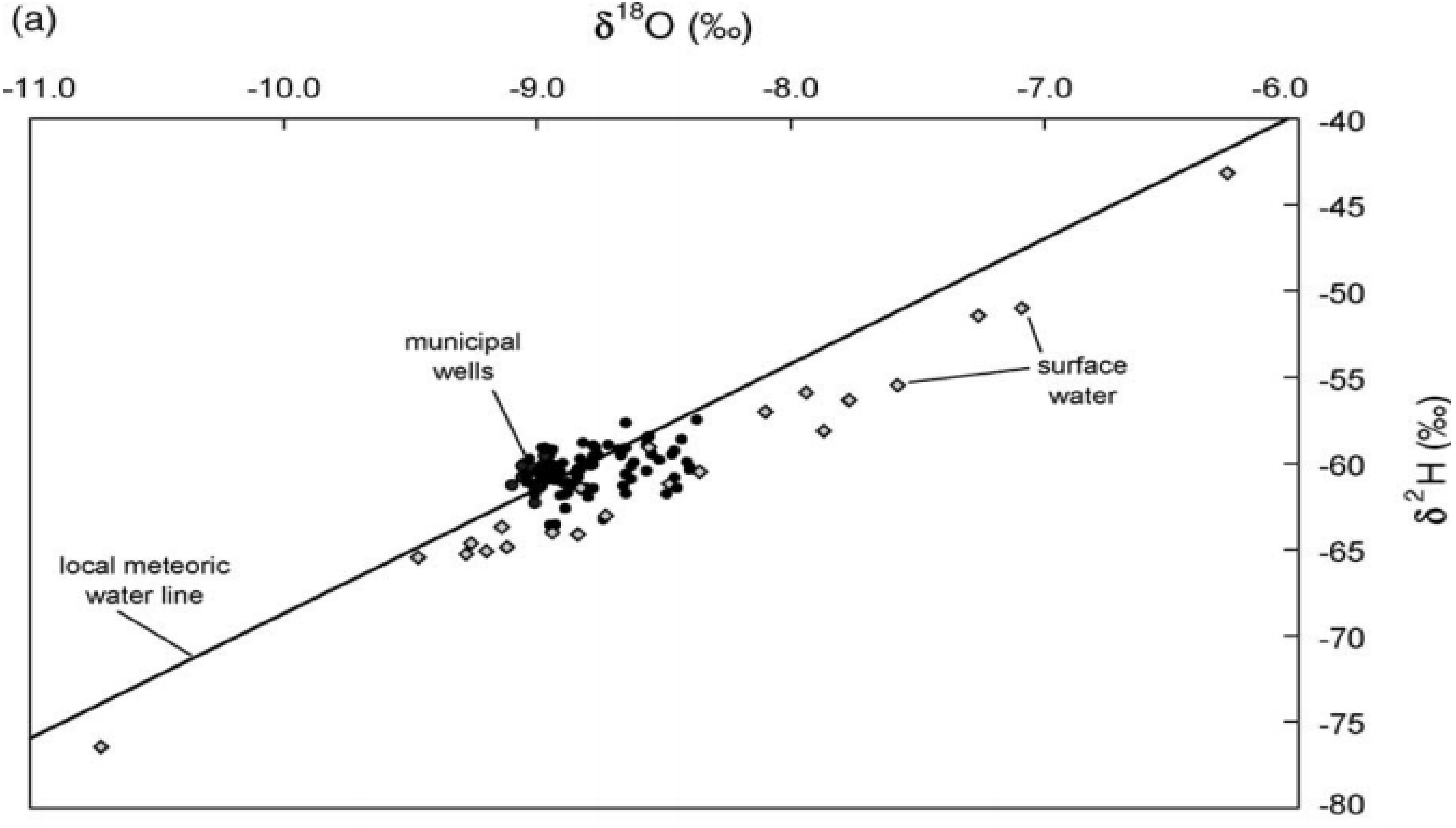


Fig. 4. Plot of the $\delta^{18}O$ time series from the municipal well, river, and piezometer installed between the river and the municipal well. Two periods are labeled in the figure: A, time required for floodwater depleted in ^{18}O to appear at the municipal well; B, time for surface water enriched in ^{18}O to appear at piezometer. River stages estimated from US Army Corps of Engineers' Pool 7 tailwater elevation data are also shown.

Table 4
Summary of time of travel estimates (river to municipal Well 24)

	Isotope time series	^{3}H–^{3}He age dating	HAV cell culture	Temperature time series	Groundwater model
Flood conditions	2 Months (2001)	NA	NA	3 Months (2002)	NA
Non-flood conditions	9 Months (2001)	11–12 Years	<1 Year	3 Months (2002)	4.5 Months

NA, not analyzed.



(a)
δ18O (‰)
-11.0
-10.0
-9.0
-8.0
-7.0
-6.0
-40
-45
-50
-55
-60
-65
-70
-75
-80
δ2H (‰)
municipal wells
surface water
local meteoric water line

The Irish Situation (Beauty and the Beast)

	No Event	"The Beast"	Drought (Beauty!!)
EC Absent	83.8%	69.2%	46.15%
EC Present	16.2%	30.8%	53.85%

Shallow Wells

Deeper Wells

Pearson Chi-Square = 7.007, P = 0.030

The Irish Situation (Beauty and the Beast)

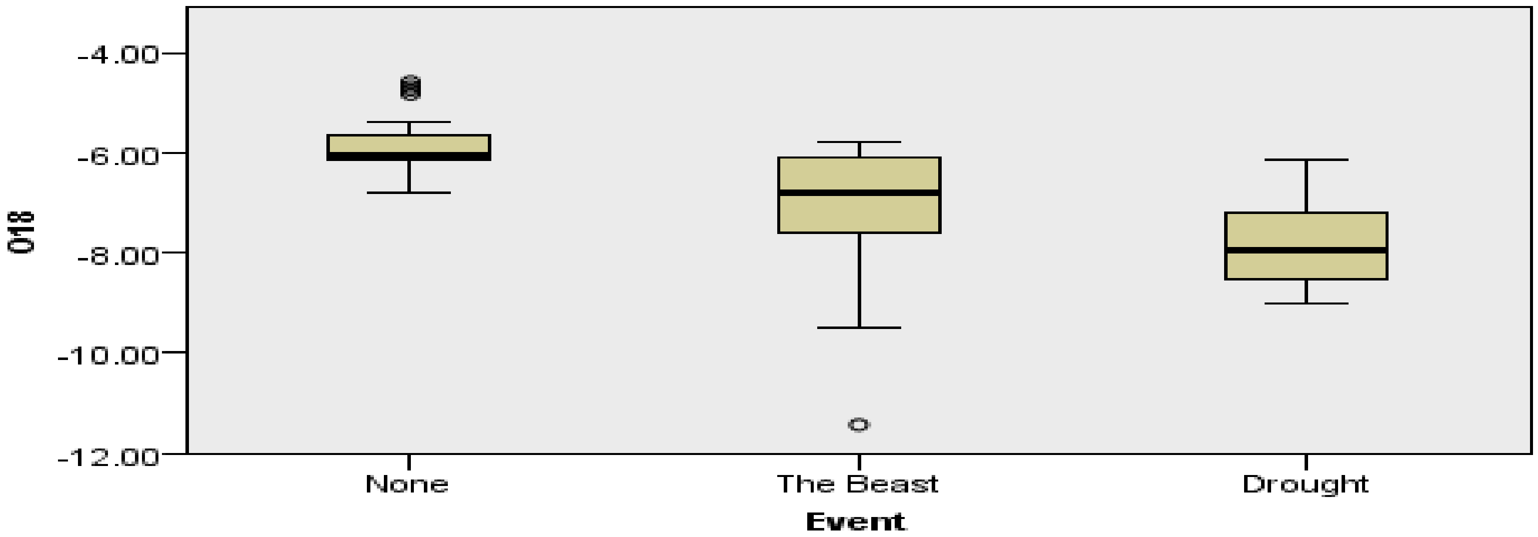
ANOVA					
O18					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	43.264	2	21.632	24.866	.000
Within Groups	59.156	68	.870		
Total	102.420	70			

Multiple Comparisons						
Dependent Variable: O18						
Bonferroni						
					95% Confidence Interval	
(I) Event	(J) Event	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
None	The Beast	1.28218*	.25483	.000	.6567	1.9077
	Drought	1.87848*	.30072	.000	1.1403	2.6166
The Beast	None	-1.28218*	.25483	.000	-1.9077	-.6567
	Drought	.59630	.32916	.223	-.2117	1.4043
Drought	None	-1.87848*	.30072	.000	-2.6166	-1.1403
	The Beast	-.59630	.32916	.223	-1.4043	.2117

*. The mean difference is significant at the 0.05 level.

The Irish Situation (Beauty and the Beast)

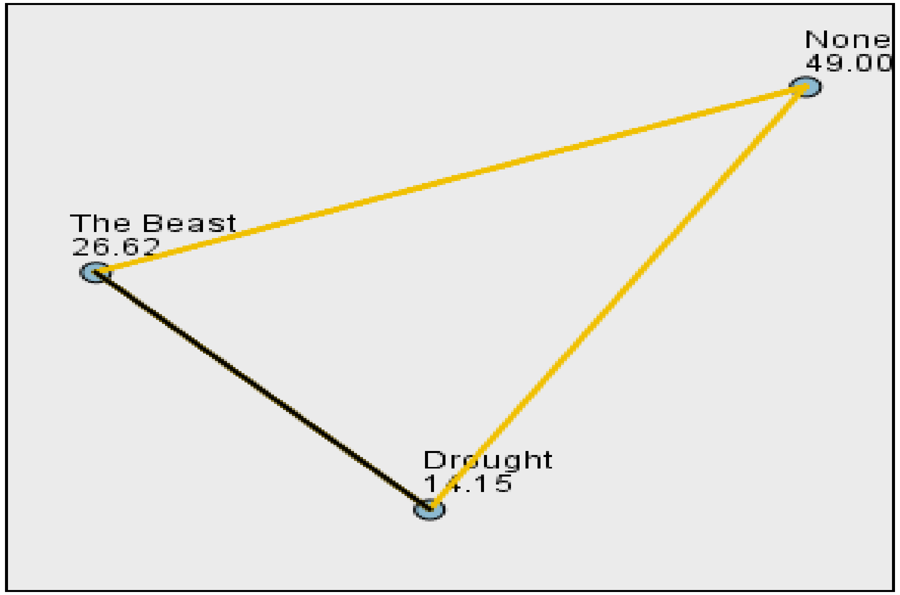
Independent-Samples Kruskal-Wallis Test



Total N	71
Test Statistic	33.584
Degrees of Freedom	2
Asymptotic Sig. (2-sided test)	.000

1. The test statistic is adjusted for ties.

“THE MODEL”
(3-D Incl EC Pres, Event, Depth and O18)



Each node shows the sample average rank of Event.

Sample1-Sample2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj.Sig.
Drought-The Beast	12.465	7.284	1.711	.087	.261
Drought-None	34.846	6.654	5.237	.000	.000
The Beast-None	22.381	5.639	3.969	.000	.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

Normal Conditions: Shallow Source (Infiltration), SW & GW

Drought Conditions: Deep Source, High Concentration (Dilution), “Real Groundwater”

Snow Conditions: Shallow Source (Top Melt), Low Concentration (Dilution), All meltwater after 24hrs

Currently, isotopes (O18) 65-75% effective at predicting E. coli presence during all events

Precipitation not employed to date

Results to date

- Rare snow event – March 2018 – opportunity to track groundwater recharge (followed by worst recorded drought)

- E-Coli encountered in depleted groundwater (~10‰) – indicating rapid recharge/ ingress

Work to complete and direction

Conclusions

- Recharge biased towards winter months
- 3-5 month recharge time
- Hydrogeology – secondary influence
- Early results indicate potential to track pathogens in ‘vulnerable’ aquifer areas

To do

- Deuterium analysis
- 2nd EPA groundwater sampling round (Oct-Dec 2018), incl. pathogen analysis
- Precipitation isoscapes
- P/GW ratios