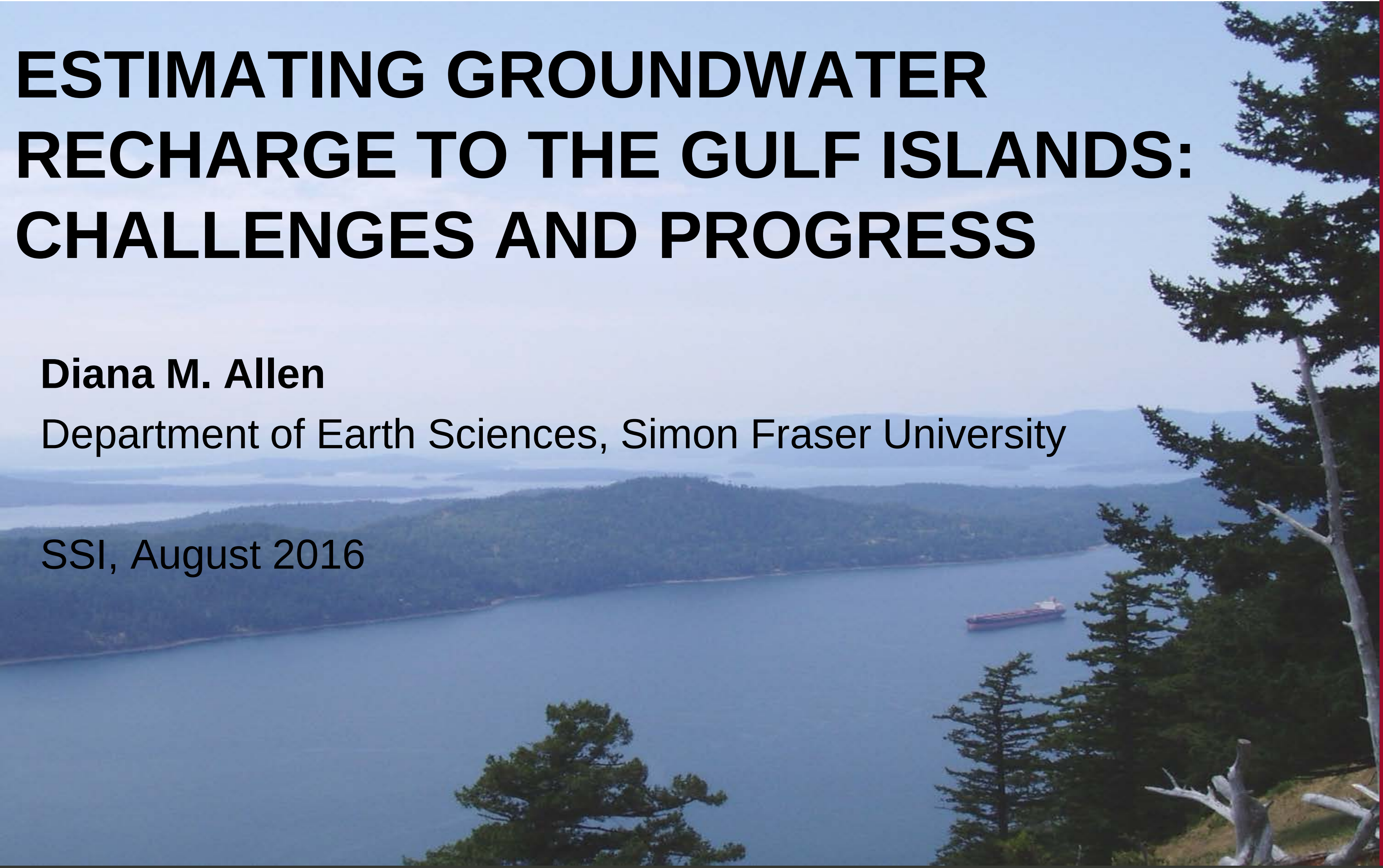
ESTIMATING GROUNDWATER RECHARGE TO THE GULF ISLANDS: CHALLENGES AND PROGRESS



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SSI, August 2016

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THINKING OF THE WORLD

- Conceptual Hydrogeological Model

- Recharge Estimation Methods
  - Direct Measurement
  - Tracer Methods
  - Water Balance Methods
  - Modeling Approaches

- Recharge Estimation on the Gulf Islands
  - 1-Dimensional Modeling
  - Coupled Land Surface – Subsurface Modeling

- Climate Variability and Change
  - Climate Variability
  - Future Change

Outline

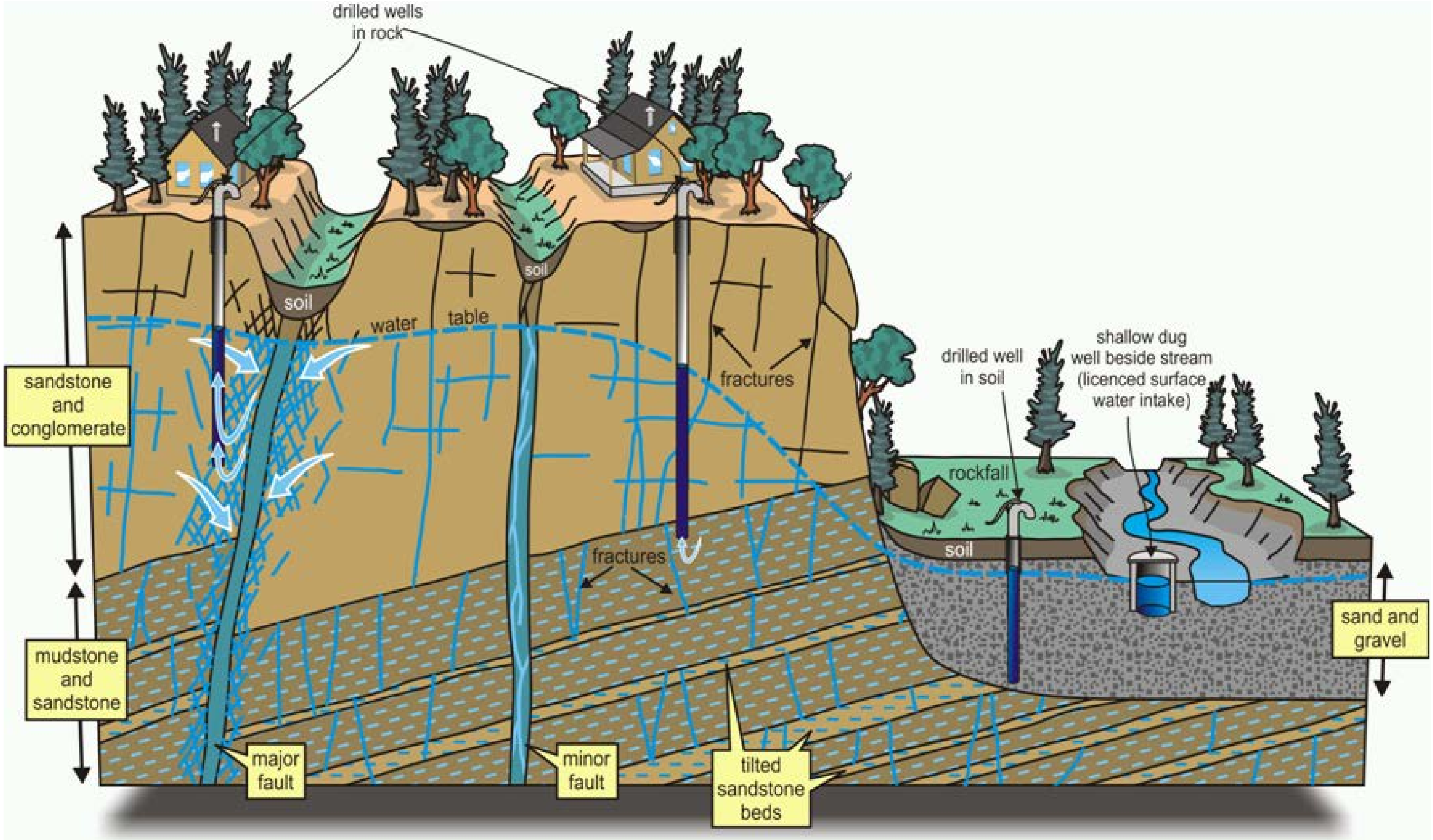

Figure courtesy of Geological Survey of Canada. Based on M.Sc. Research (SFU Earth Sciences) by Mackie (2002) and Surrette (2006).

The Conceptual Hydrogeological Model

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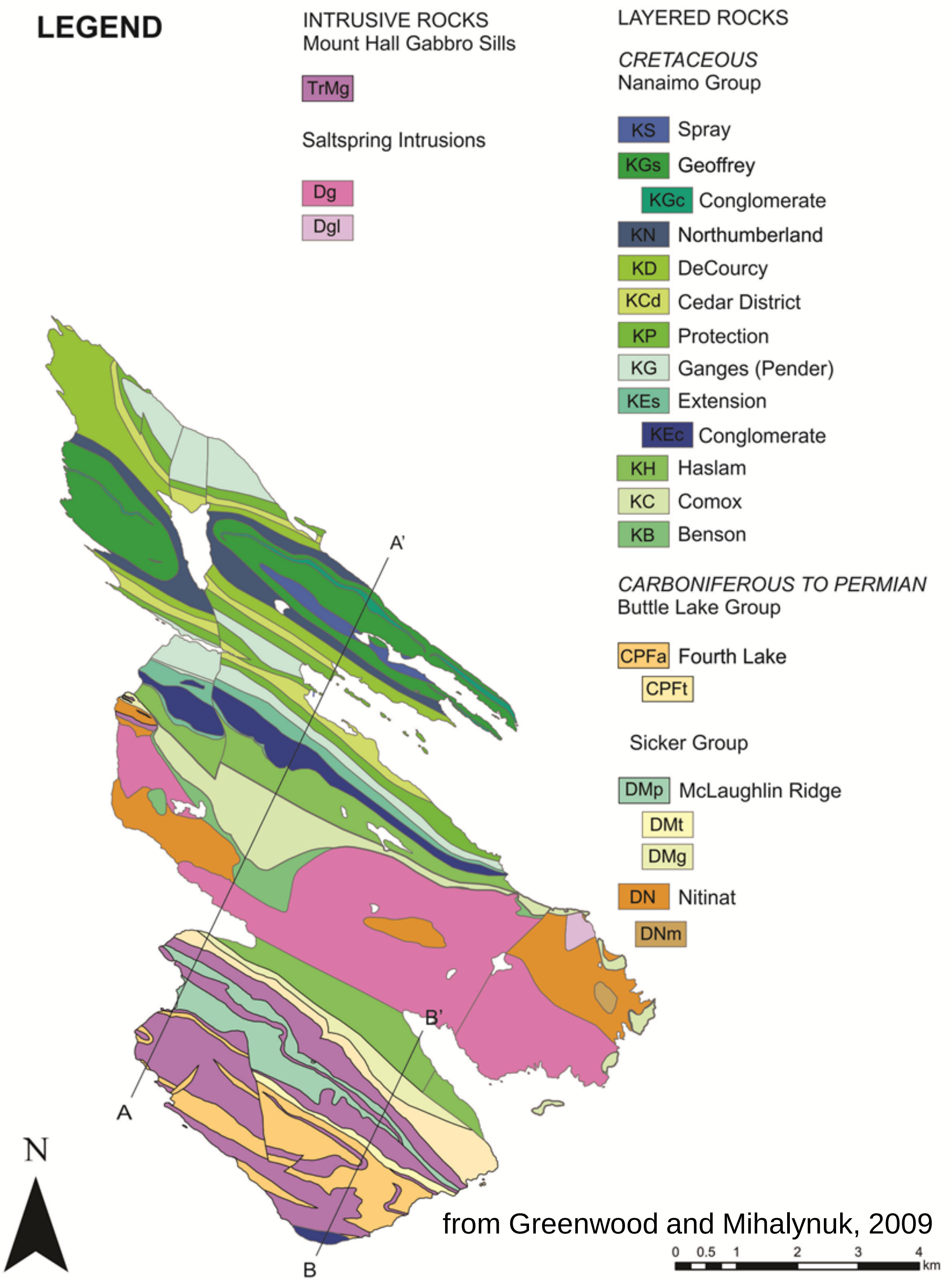
Bedrock Geology

- The geology of Salt Spring is a bit different:
  - Two dominant rock types:
    - sedimentary (Nanaimo Group) and
    - igneous.
- The bedrock throughout the southern Gulf Islands has been extensively folded and fractured (Journeay and Morrison, 1999).



from Greenwood and Mihalynuk, 2009

A fractured bedrock aquifer flow regime is more influenced by structure than by lithology.

Sedimentary bedrock aquifers in the Gulf Islands have been divided into hydrostructural domains (Mackie, 2002) according to their relative fracture network permeability.

  - ‘highly’ fractured interbedded mudstone and sandstone (IBMS-SS),
  - ‘less’ fractured sandstone (LFSS), and
  - fracture zone (FZ).
- The igneous rocks are also fractured, and so they too constitute a hydrostructural domain: “igneous”
- Hydraulic test data (pumping tests, tidal response tests) were therefore grouped according to hydrostructural domain – NOTE: FZ domain was not considered.

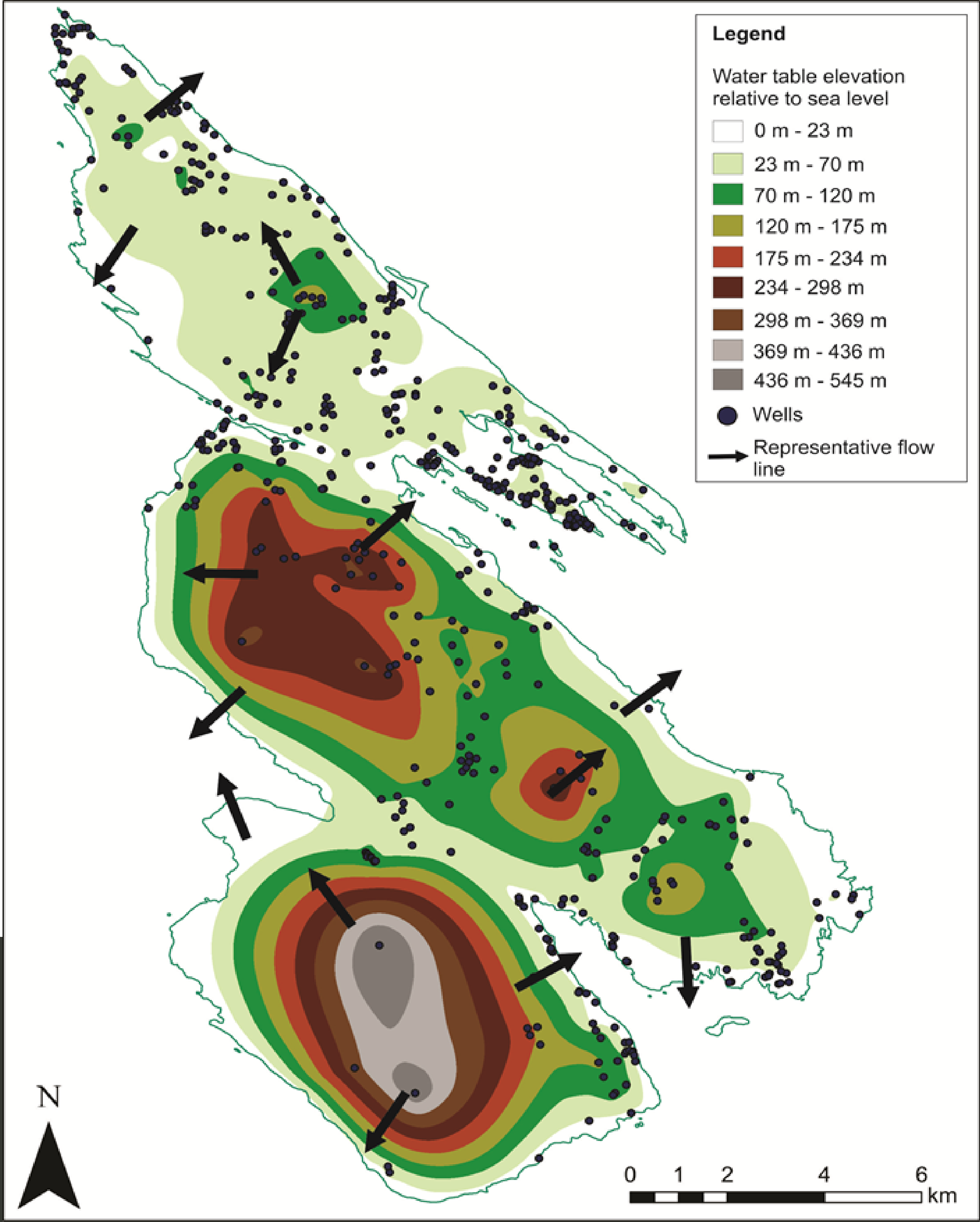
Hydrostructural Domains

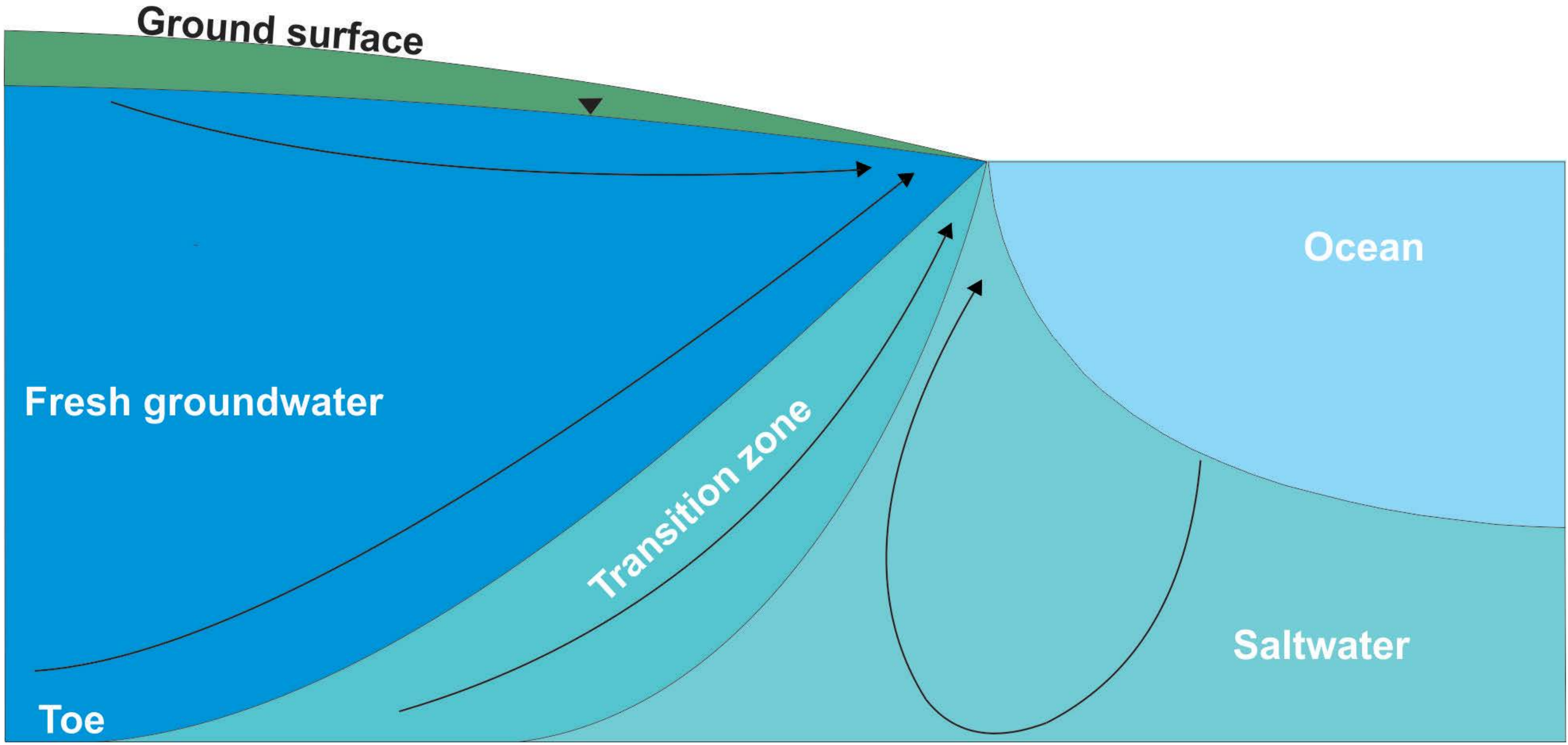
	Lithology	
Location	Sandstone	Mudstone
	Ave T (m^2/s)	
Salt Spring	1.4E-05	1.6E-05
Gulf Islands	1.9E-05	1.6E-05
	Ave K (m/s)	
Salt Spring	2.4E-07	3.6E-07
Gulf Islands	2.5E-07	4.7E-07

Hydraulic Properties

GW Flow

- Representative groundwater flow lines drawn simply on the basis of water table topography.
- GW flows from high elevation to low at a regional scale.
- Locally, GW can be expected to discharge into streams and lakes.
- Differences in flow line direction due to geological contrasts are not reflected in this map.
- Flow lines do not represent the likely pathways along major faults.





Coastal Aquifers

Climate

Precipitation

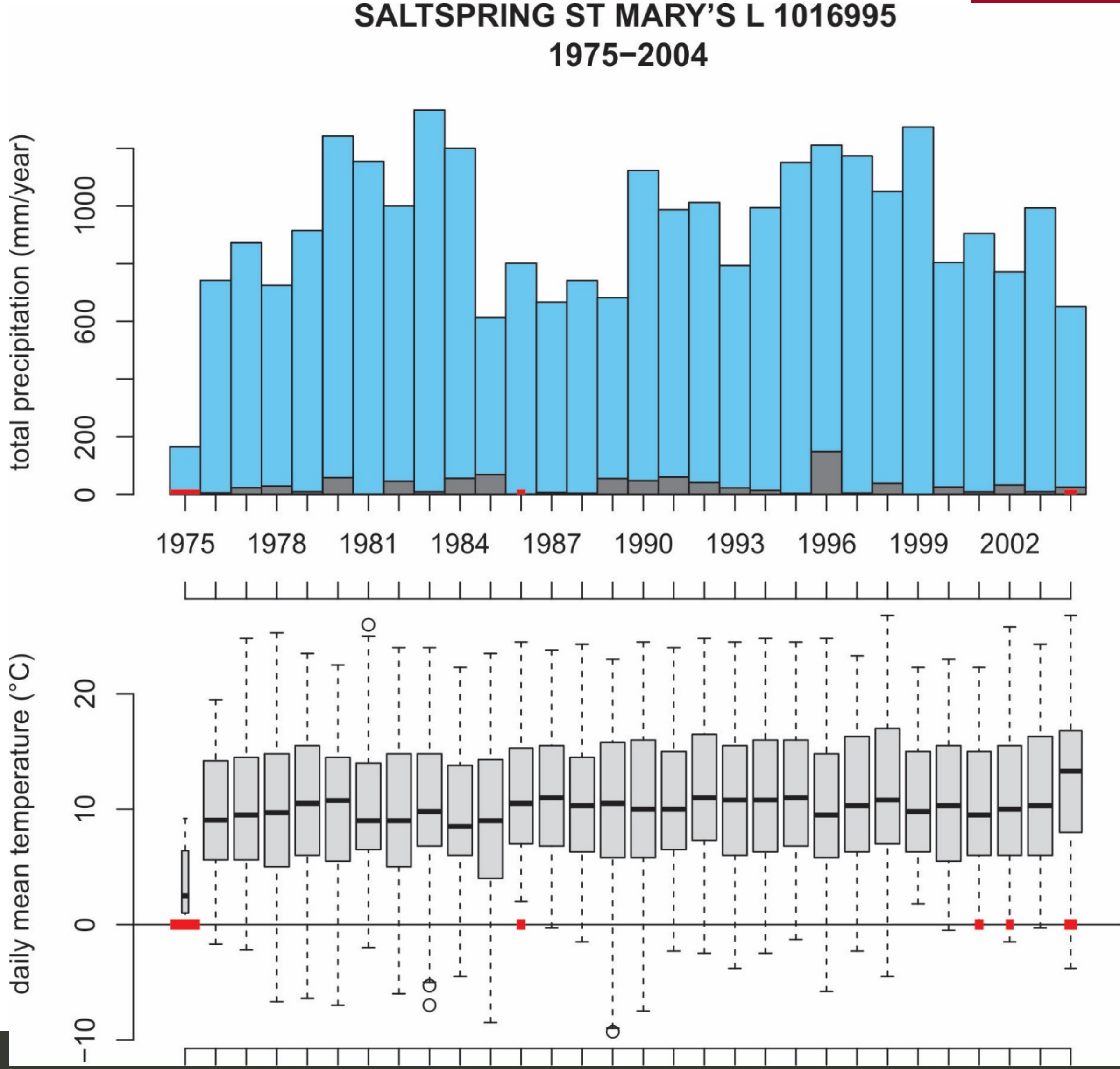
Mean annual precipitation ranges from 658mm to 983mm. Most falls as rain.

- On average, the lowest monthly precipitation occurs in July (~23mm), and the maximum in November (~143mm).

Temperature

Mean monthly temperature ranges from:

- 3.66° C to 4.23° C from November to January.
- 16.98° C to 18.39° C from June to August.



SALTSPRING ST MARY'S L 1016995
1975–2004

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Conceptual Model for Recharge

Dynamic process

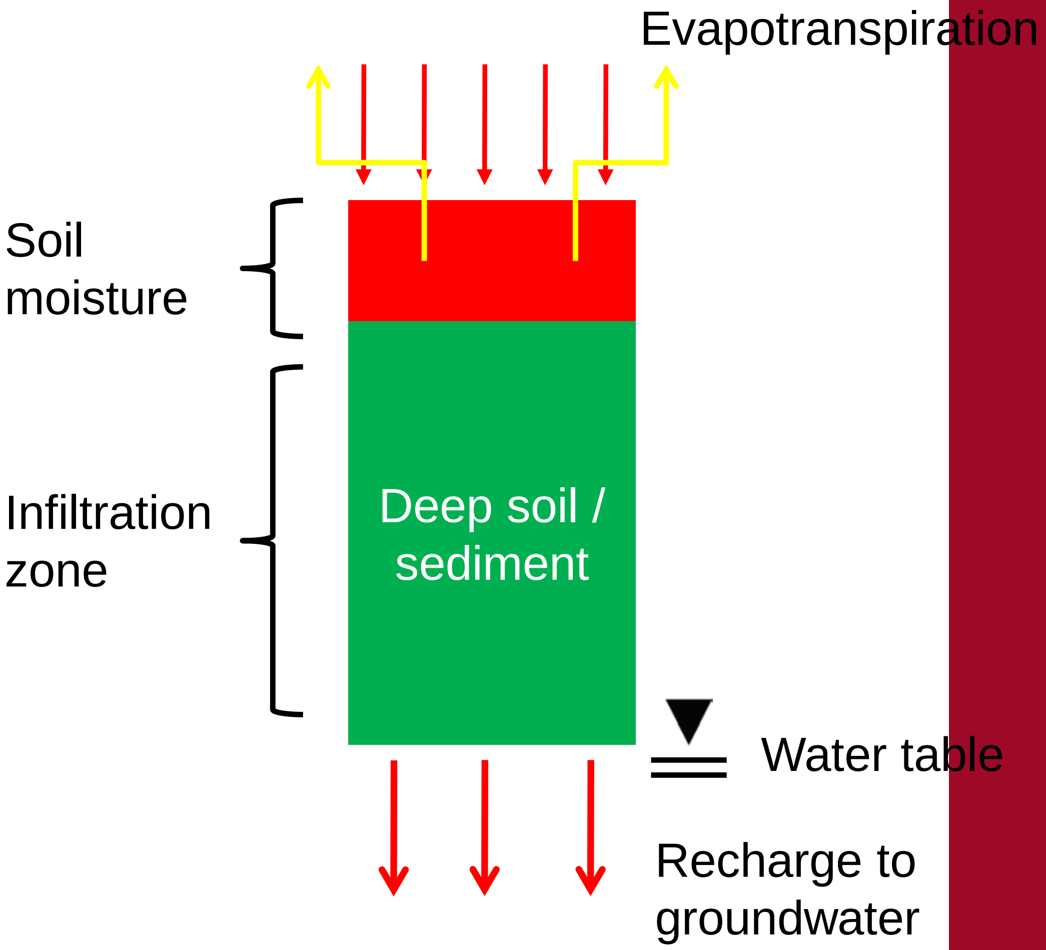
Depends on climatology

- Precipitation
- Temperature
- Wind
- Humidity

Depends on land cover

- vegetation

Depends on geology



Evapotranspiration

Soil moisture

Infiltration zone

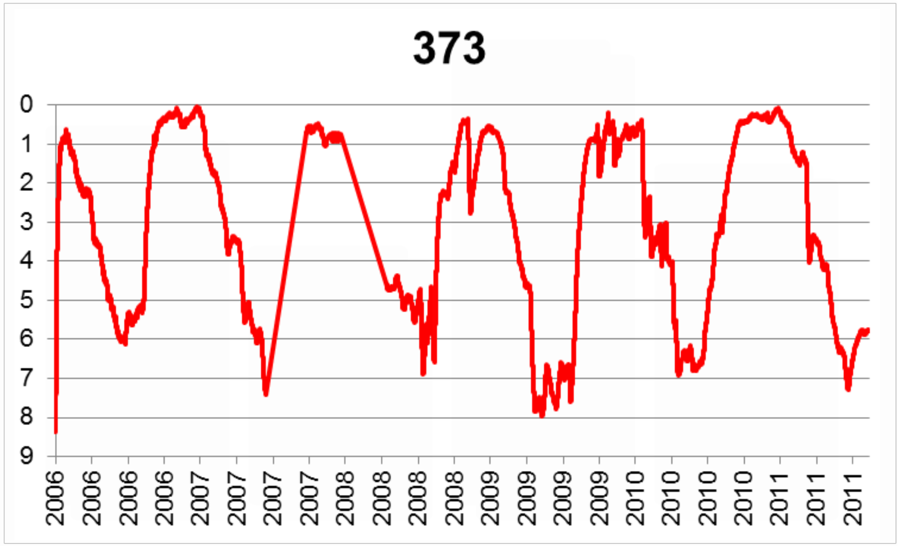
Deep soil / sediment

Water table

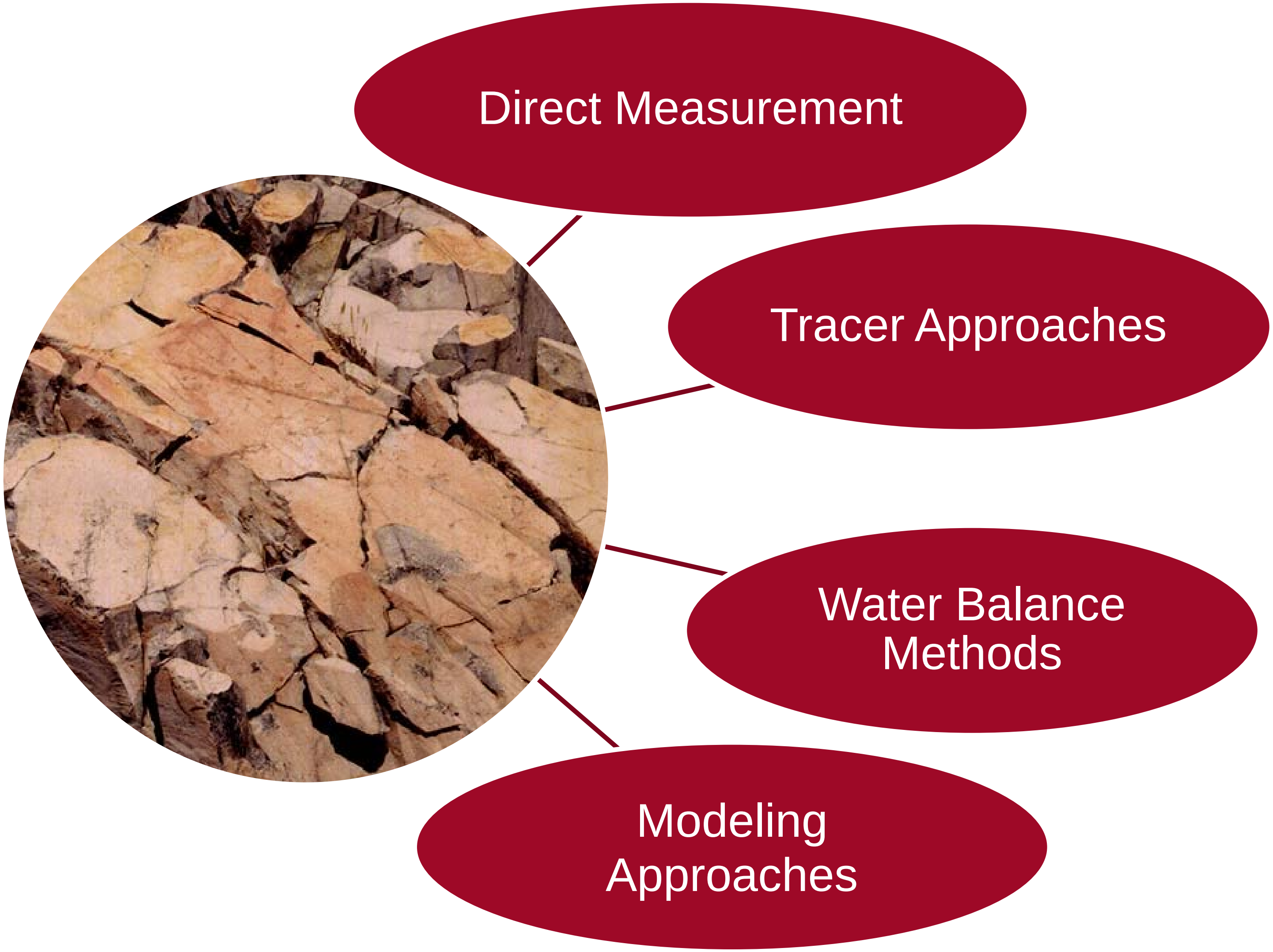
Recharge to groundwater

Groundwater Level Responses

- Groundwater is recharged locally from precipitation.
- Most recharge occurs in the late fall and winter months.
- Aquifers respond to recharge (and discharge) cycles by changing water levels.
- The magnitude of the fluctuations is determined by a combination of the geology and the climate



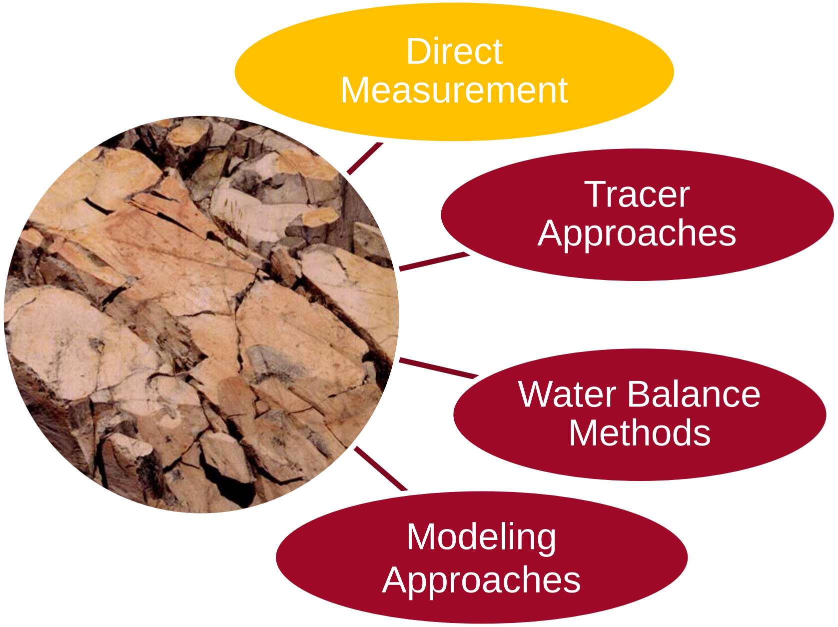
Recharge Estimation Methods



- Direct Measurement
- Tracer Approaches
- Water Balance Methods
- Modeling Approaches

Direct Measurement

- Direct measurement of recharge is very difficult, particularly in fractured rock.
- The methods are mostly based on measuring the moisture content
- Weighing Lysimeters
  - Weigh soil and measure outflow of seepage at different times.
  - Only local estimates obtained
  - Very difficult to install in fractured rock.
- Neutron or TDR probes
  - Similarly measure moisture content, but do not measure fluxes.



Direct Measurement

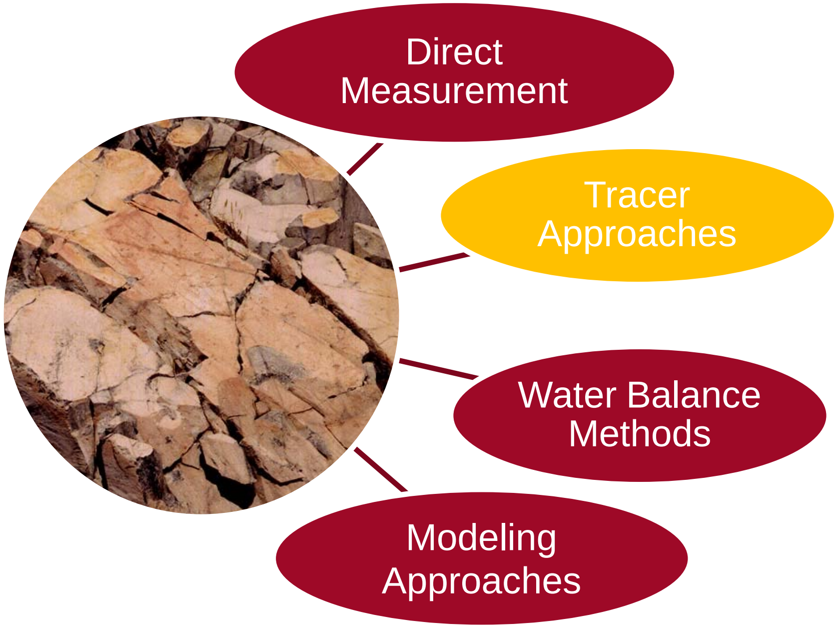
Tracer Approaches

Water Balance Methods

Modeling Approaches

Tracer Approaches

- Environmental Tracers are able to trace water movements over long time periods.
- Chloride method
  - Conservative tracer which is used to estimate ET assuming no runoff.
  - Works well if there are no other sources of chloride!
- Tritium and He/^{3}H
  - Acts as a time marker due to its radioactive decay.
  - Porosity is needed – difficult in fractured rock.
  - Mixing models are needed.


Direct Measurement

Tracer Approaches

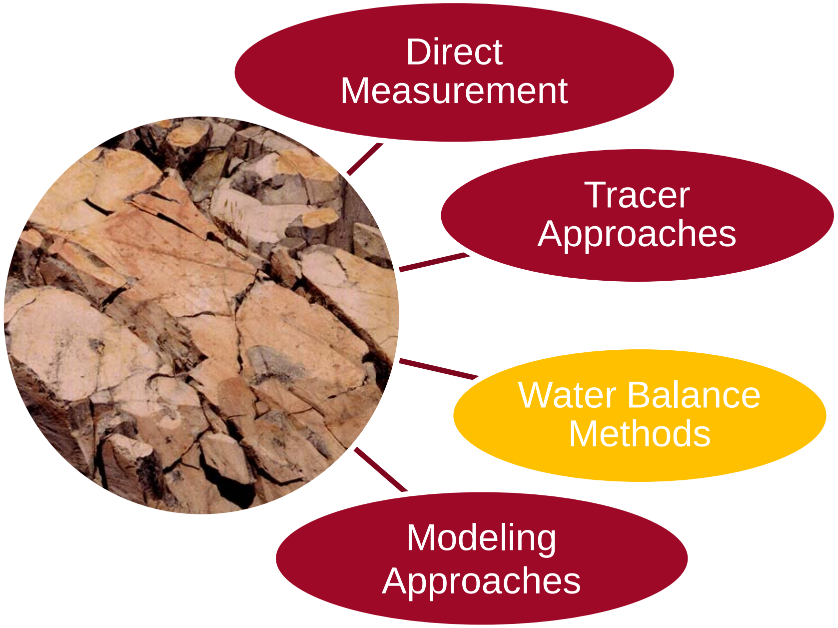
Water Balance Methods

Modeling Approaches

- Stable Isotopes (^{2}H, ^{18}O)
  - Used to establish mixing ratios
  - Detects evaporation but not transpiration
- Several other tracers (^{14}C, Br, ^{36}Cl, CFCs, SF_6)

Water Balance Methods

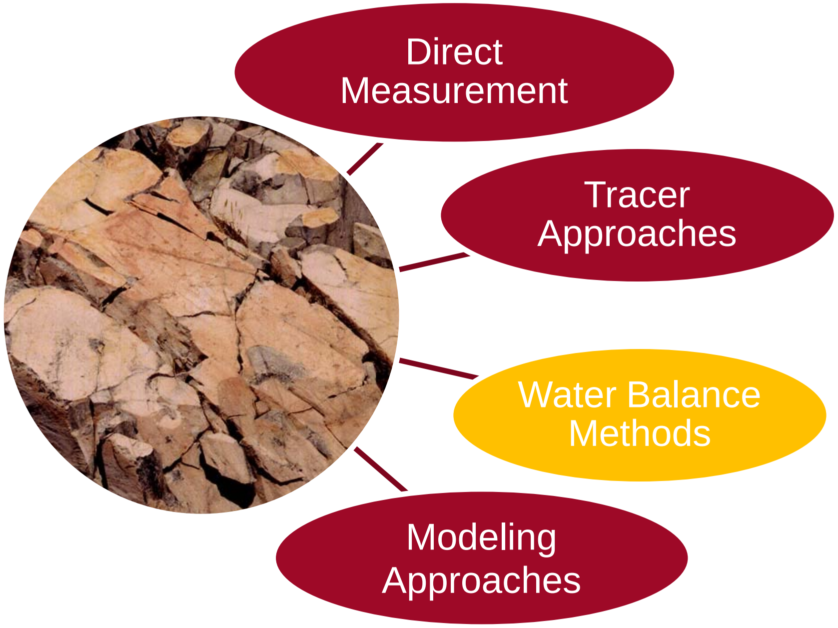
- Recharge can be approximated from the water balance equation if the other components of the water balance are known:
    - P can be reasonably estimated
    - For islands, Q_{in} and GW_{in} are zero
    - ET is very difficult to estimate, however.
    - Q_{out} and GW_{out} along the coast are difficult to estimate.



$$R = (P + Q_{in} + GW_{in}) - (ET + Q_{out} + GW_{out}) \cancelto{0}{\pm \Delta S_{GW} \pm \Delta S_{SW}}$$

Water Table Fluctuation Method

- The water table rise is the clearest indicator or recharge if all abstractions remain unchanged and atmospheric effects can be ruled out.
- $R = S_y\, \Delta H / \Delta t + D$
  - S_y is the specific yield. Very difficult to estimate, particularly for fractured rock.
  - $\Delta H / \Delta t$ can be read of a hydrograph.
  - D is the drainage (often not accounted for in this method), but hard to estimate.

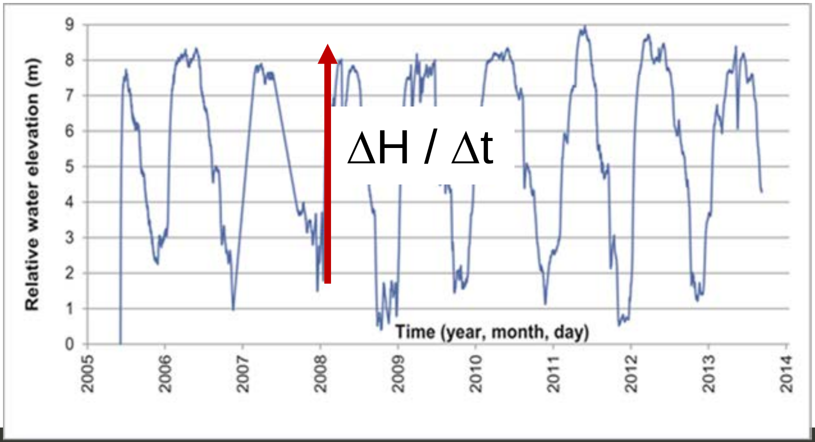


Direct Measurement

Tracer Approaches

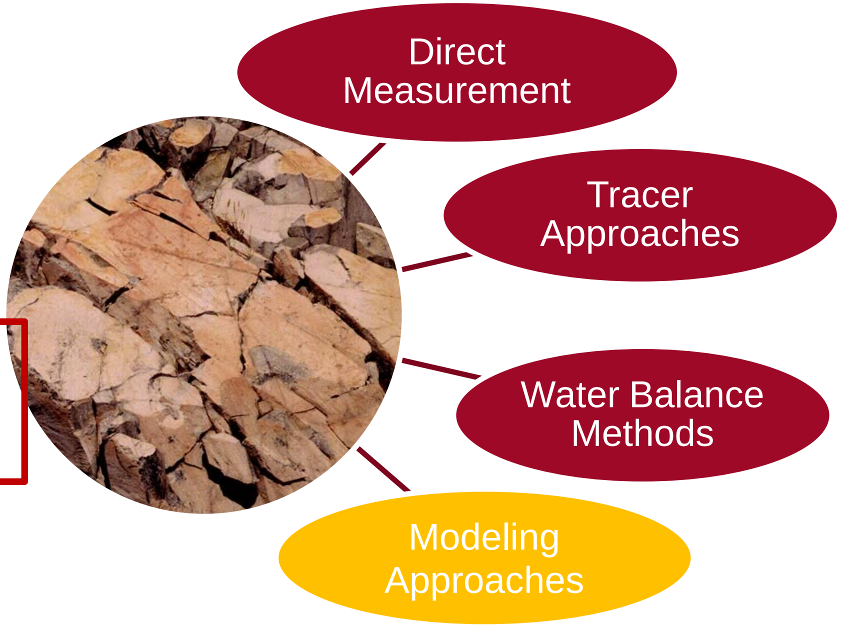
Water Balance Methods

Modeling Approaches



Modeling Approaches

- Various modeling approaches
- Application of Darcy's Law
  - Estimate the flux from gradient and K.
- Vertical percolation models - HELP
  - 1-dimensional
- Groundwater flow and transport models
  - Difficult to calibrate
  - K and recharge linked
- Coupled land surface – subsurface models – MIKE SHE



Direct Measurement

Tracer Approaches

Water Balance Methods

Modeling Approaches

Recharge Estimates

Study	Study Area	Method	Recharge Estimate (% of Precipitation)	
			Mean	Range
Foweraker (1974)	Mayne Island	nr	3	nr
Hodge (1977)	SS Island	WTF method	2.6^a	1-4.4^a
Appiah-Adjei (2006)	Gulf Islands	HELP	45	20-60
Denny et al. (2007)	Gulf Islands	HELP	37^b	12-63^b
Liteanu (2003)	Saturna Island	2D GW modeling	20	10-50
Trapp (2011)	Saturna Island	2D GW modeling	56	5-56
Scibek et al. (2013)	Gabriola Island	WTF method	10^c	1-20^c
McKoen and Allen (np)	Gulf Islands	WTF method with D (Sy=5%)	~30	-
Burgess (in progress)	Gabriola Island	MIKE SHE	20	10-25

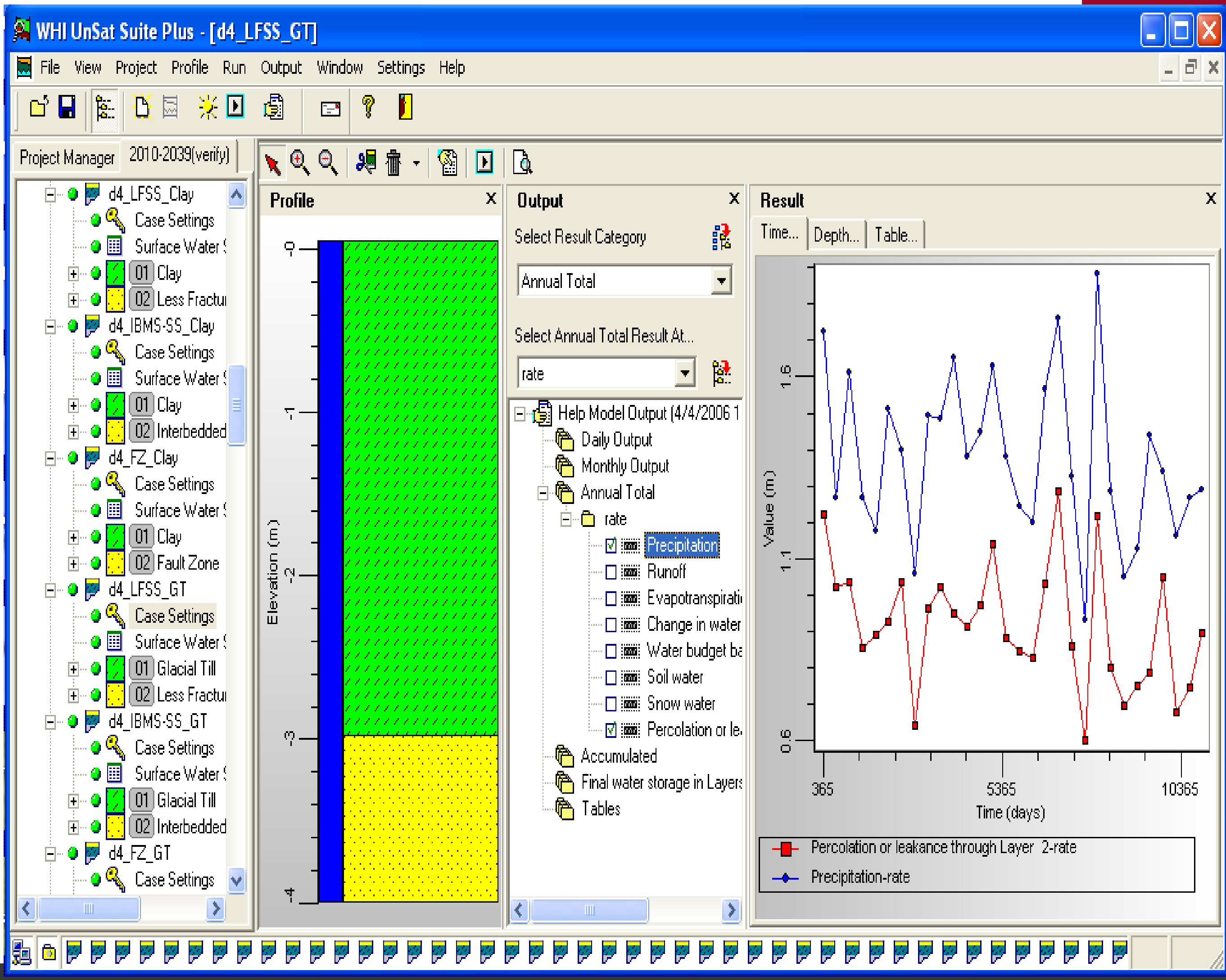
[a] The mean and range are estimated based on the total precipitation at St. Mary Lake weather station in 2012 and the amount of precipitation recharging the aquifer used by Hodge (1995) (e.g. (25.4 mm / 974.2 mm) * 100 = 2.6 %);

[b] This estimate is from a series of models incorporating surficial sediment and bedrock within a modeled soil column;

[c] Values estimated for Gabriola Island using the Water Table Fluctuation (WTF) method; nr: method not reported.

- Climate data are used drive the
- USEPA HELP hydrologic model

- 48 percolation vertical columns
  - 4 aquifer media classes
  - 4 soil media classes
  - 4 water depth classes

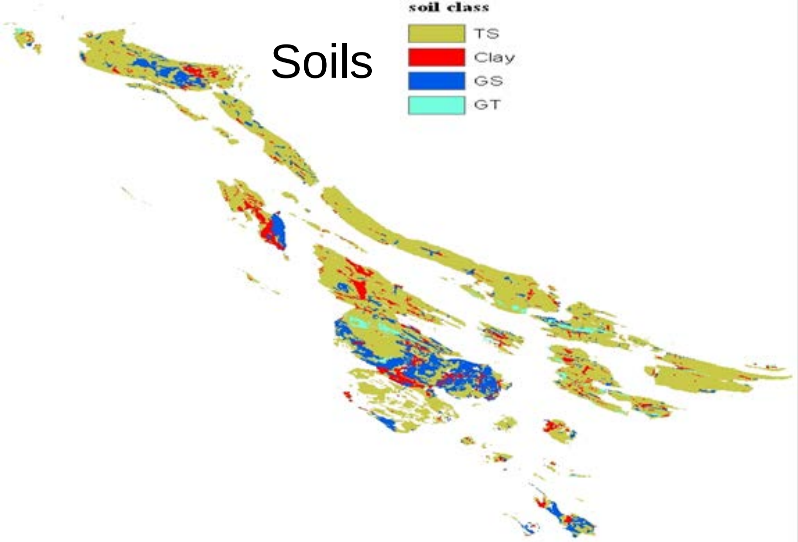


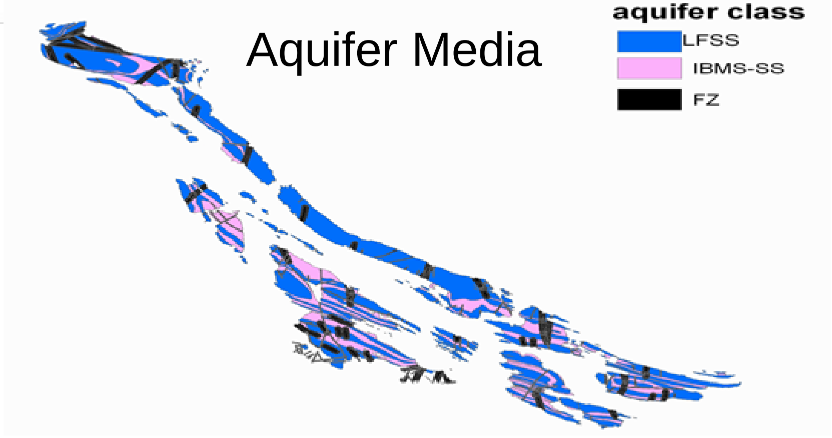
Select Result Category: Annual Total

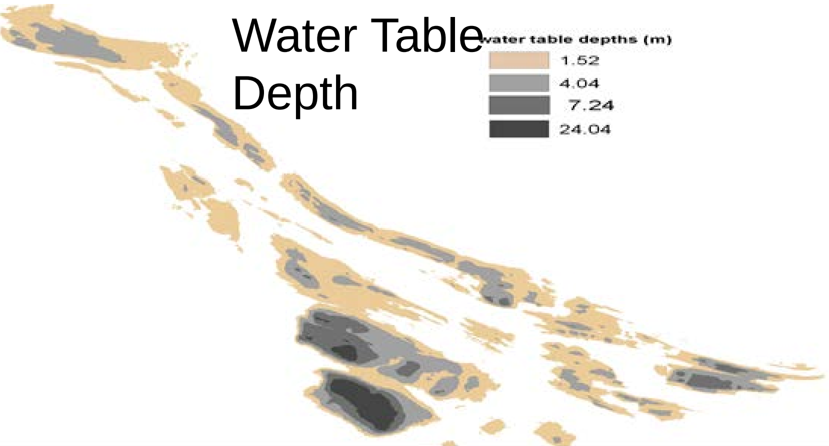
Select Annual Total Result At...: rate

1D Recharge Modeling

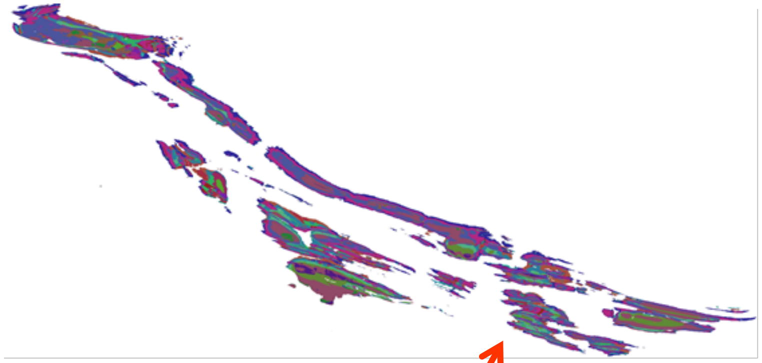
Spatial recharge was mapped by modeling recharge for different zones

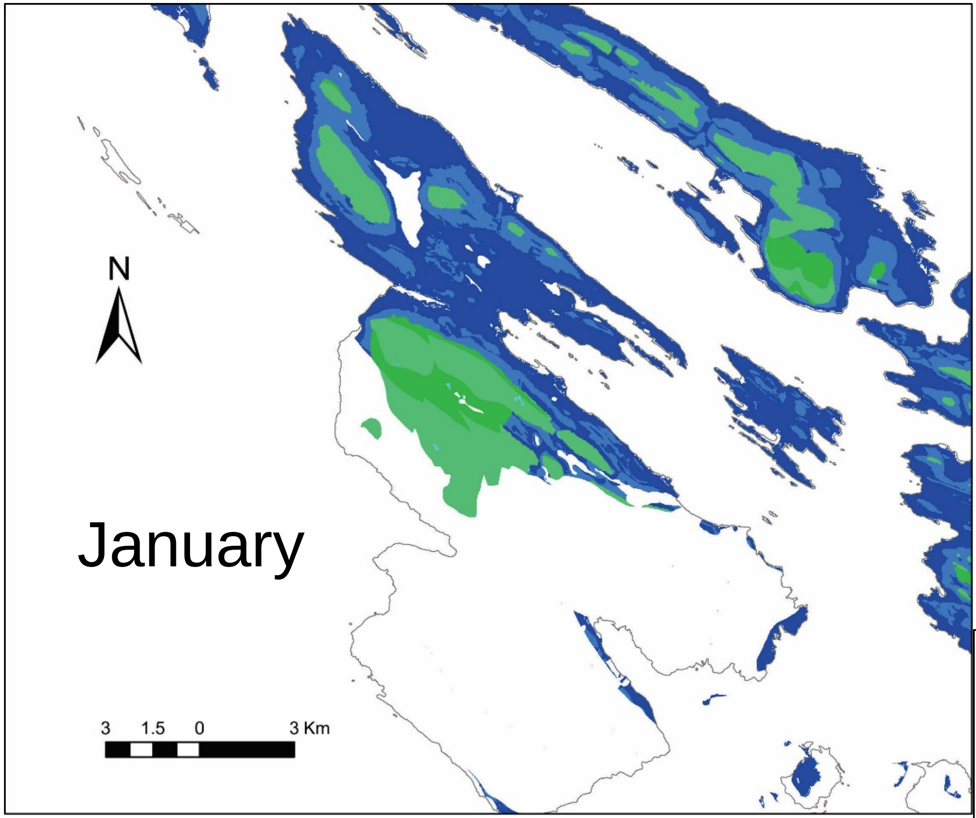

Soils

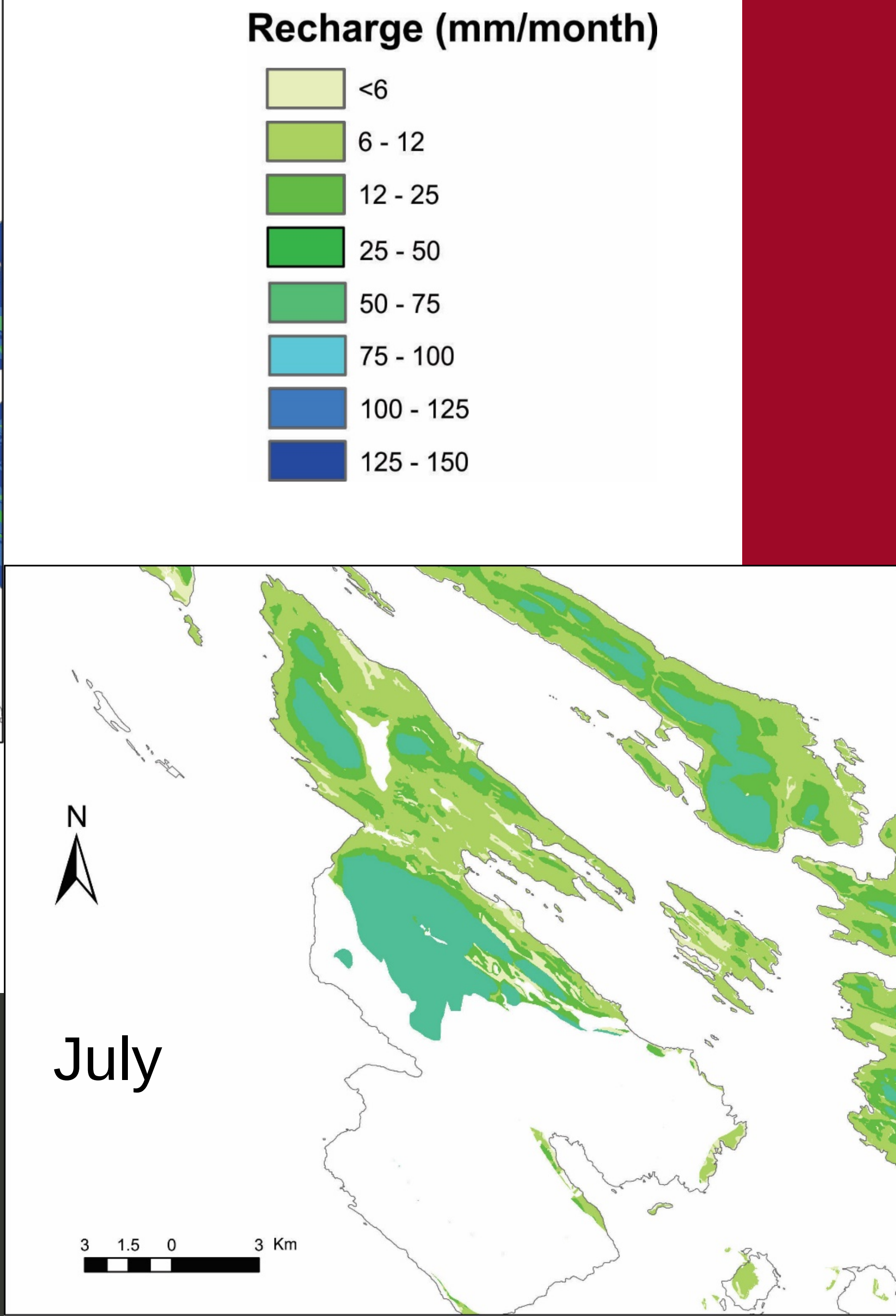

Aquifer Media


Water Table Depth

Recharge "zones"







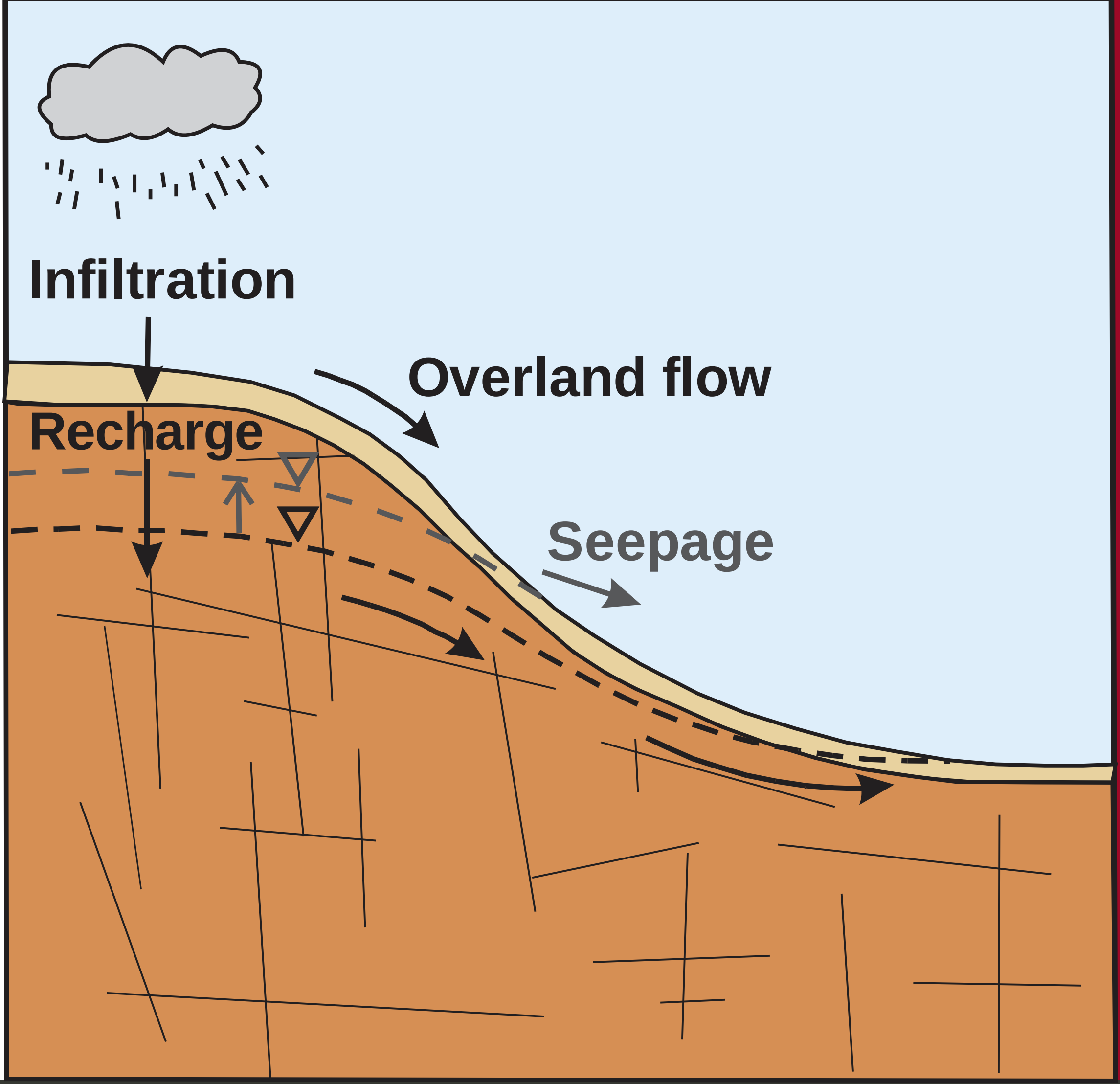
Values are over-estimated, but they show spatial and seasonal variability on Salt Spring Island (sedimentary bedrock only)

1. Mean annual recharge across the Gulf Islands was estimated at 414 mm/year (45% of precip).
2. Spatially distributed mean annual recharge was estimated to be in the range of 184 to 537 mm/year (~20-60% of precip).
3. Over half of precipitation from December to June contributes to recharge, while less than 40% contribute to recharge from July to November.

4. HELP appears over-estimate recharge.
   - This happens because the water table is placed at a fixed depth and cannot rise.
   - In reality, the water level rises until it can rise no more without generating saturated overland flow.
   - This suggests an alternative conceptual model for recharge is needed.

HELP Modeling Conclusions

- As recharge occurs, the water table rises, generating seepage along the slopes, which limits the amount of water that can recharge the groundwater system.



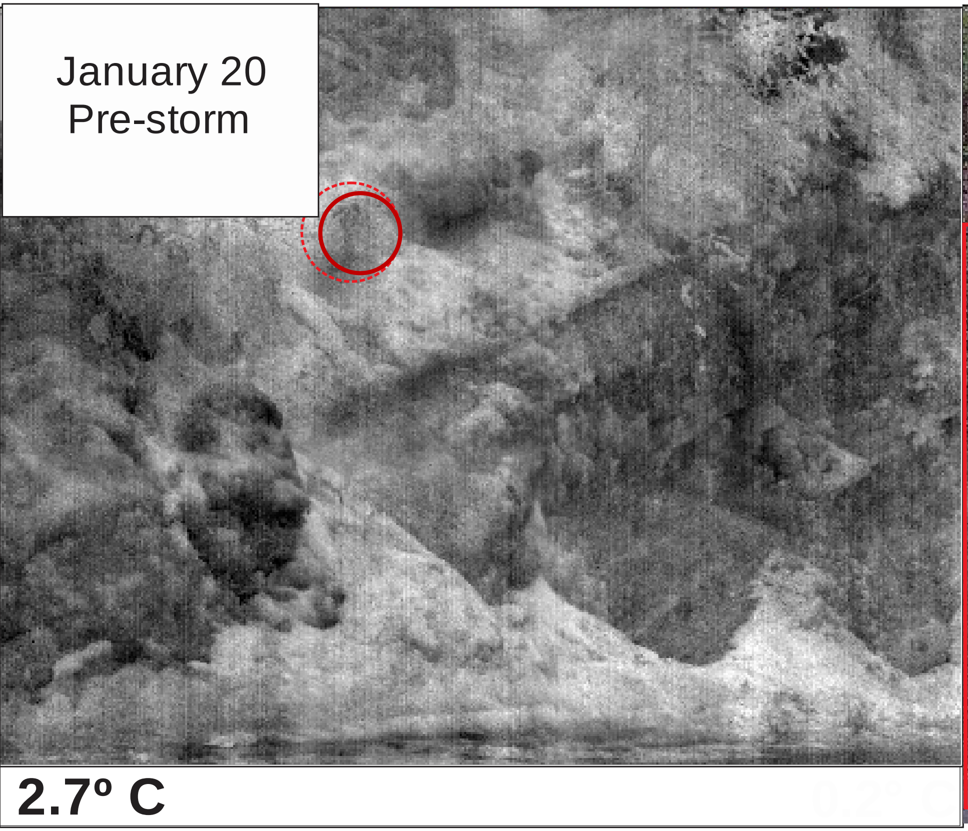
New Conceptual Model for Recharge

- Thermal infrared imaging was carried out at various times over the past year during:
    1. Dry summer following a period with little rainfall.
    2. Early fall after a long period with no rainfall
    3. Late fall shortly after rain events
    4. Prior, during and following a very heavy rain event.
- The idea was to try and capture information on the GW level rise and seepage in response to rain events at different times during the year.

Thermal Imaging

Thermal Infrared Images

Groundwater Level High – Ground Saturated



Rathay (M.Sc. in progress)

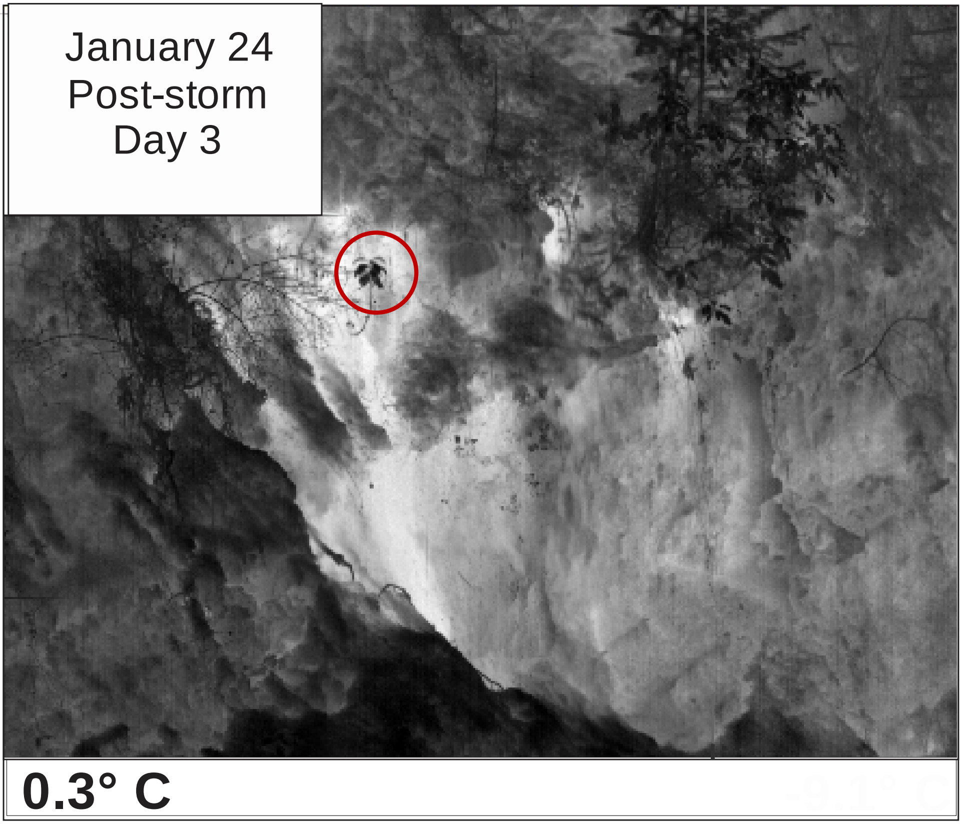
Thermal Infrared Images

January 22
Post-storm
Day 1

Rathay (M.Sc. in progress)

Thermal Infrared Images

Rathay (M.Sc. in progress)



January 24
Post-storm
Day 3

Thermal Infrared Images

Rathay (M.Sc. in progress)

1. Little to no seepage was observed when a rain event occurred after a long period with no rain (i.e. summer and fall).
2. It was only once the water table was relatively high, was seepage observed.
3. Seepage along bedding planes was initiated very rapidly following the onset of precipitation; likewise seepage dissipated rapidly.
4. Attests to the high permeability and low storage of these aquifers.

Thermal Imaging Observations

- The generation of seepage faces during rain events at particular times of the year, suggests that an alternative approach is needed to model recharge.
- The model needs to be multi-dimensional, transient and capable of solving the complex set of equations that govern evapotranspiration, overland flow, and recharge.

Land Surface – Subsurface Modeling

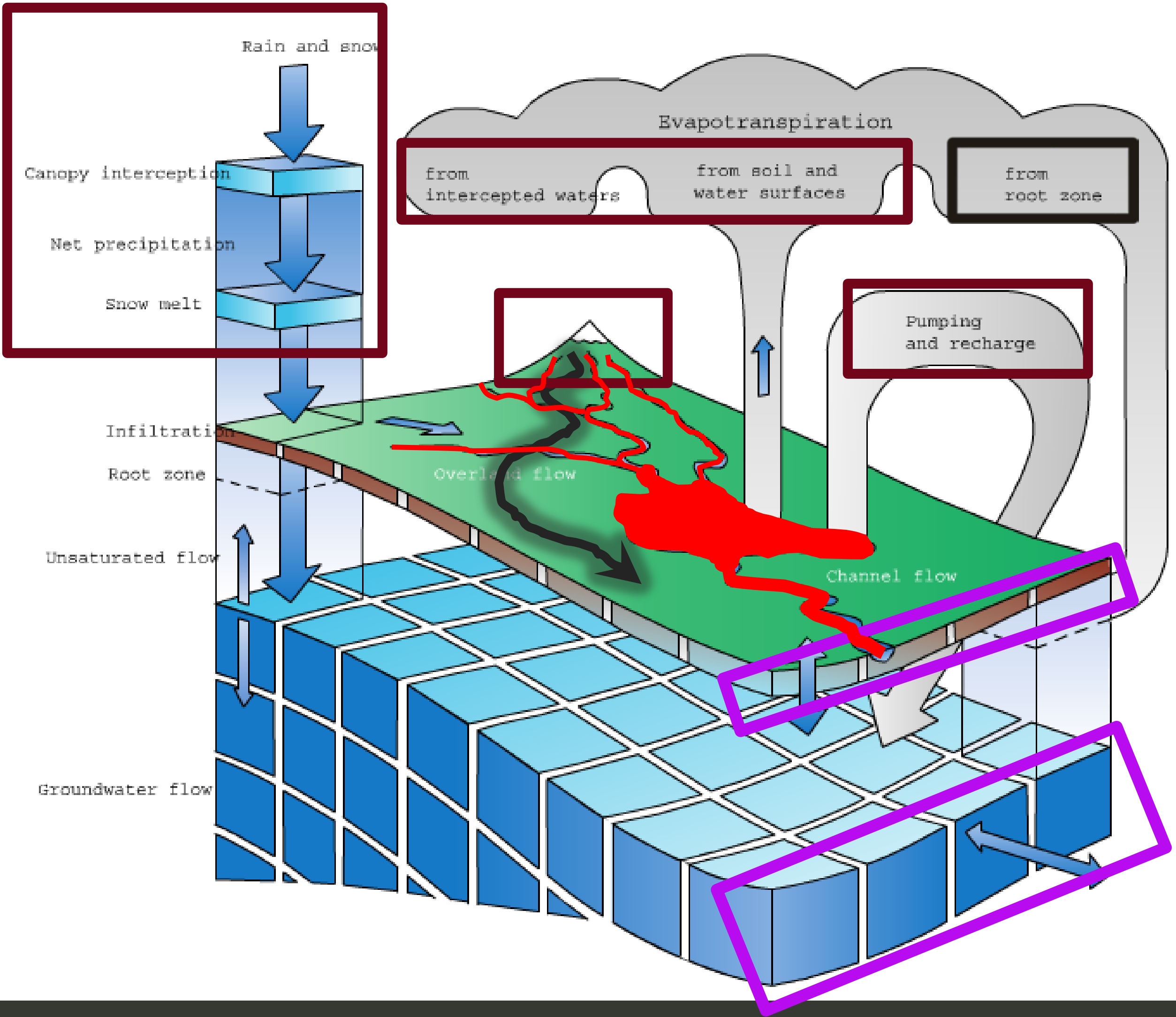
Fully Dynamic Hydrologic Model

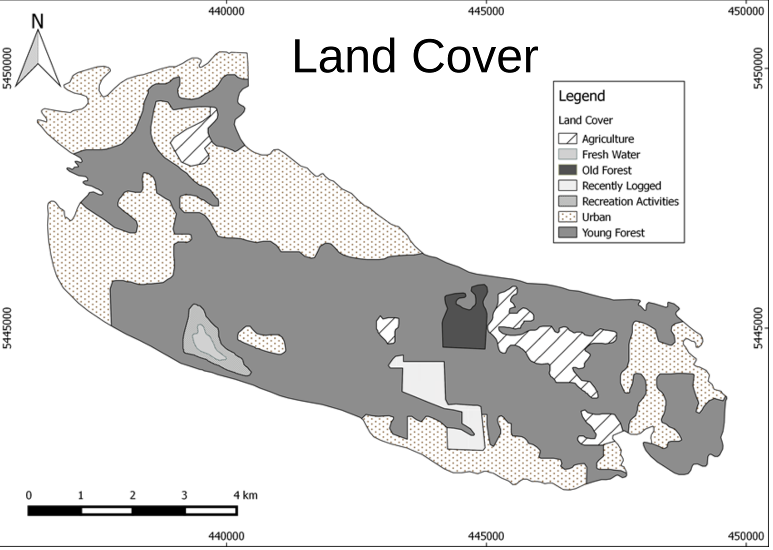
1. Climatic Datasets
- Precipitation
- Temperature
- Lapse Rates
- PET

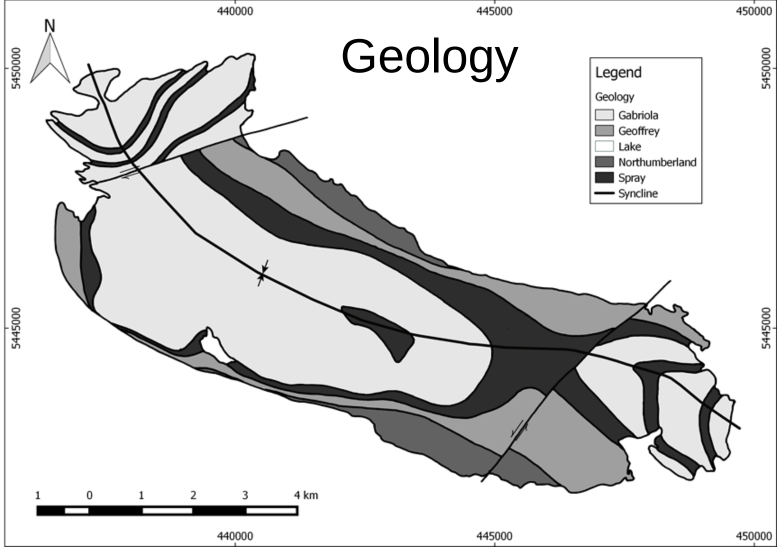
2. Land Surface Classification Datasets
- Leaf Area Index
- Overland Flow

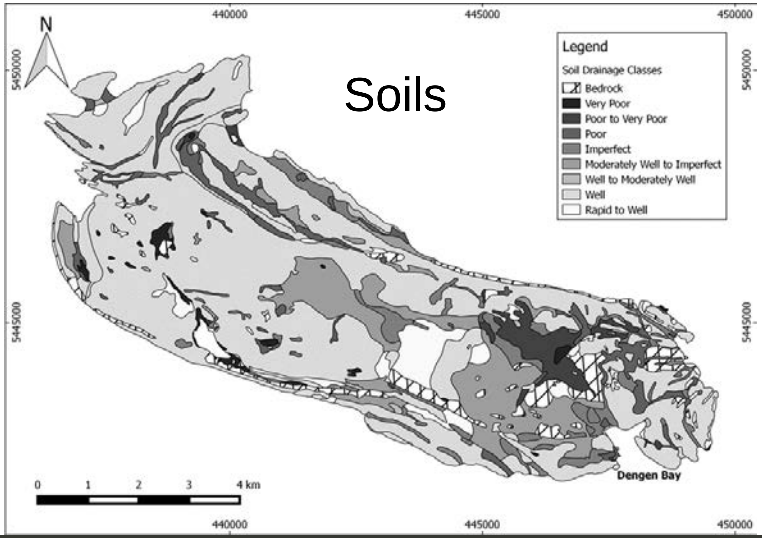
3. Geological Datasets
- Unsaturated zone geology (soils)
- Saturated zone geology (alluvium and bedrock)
- Water use (pumping)

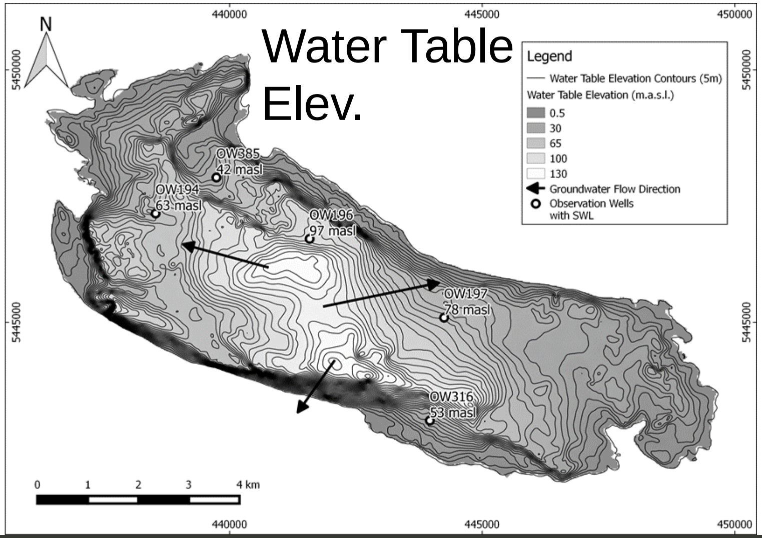
4. Surface Water Datasets
- River and lake morphology
- Water use (diversion)




Land Cover


Geology


Soils


Water Table Elev.

Spatial Datasets

Burgess (M.Sc. In progress)

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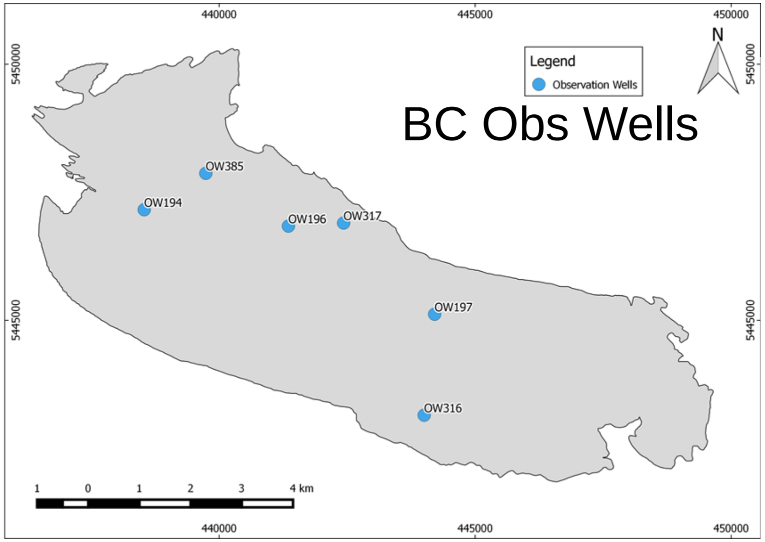
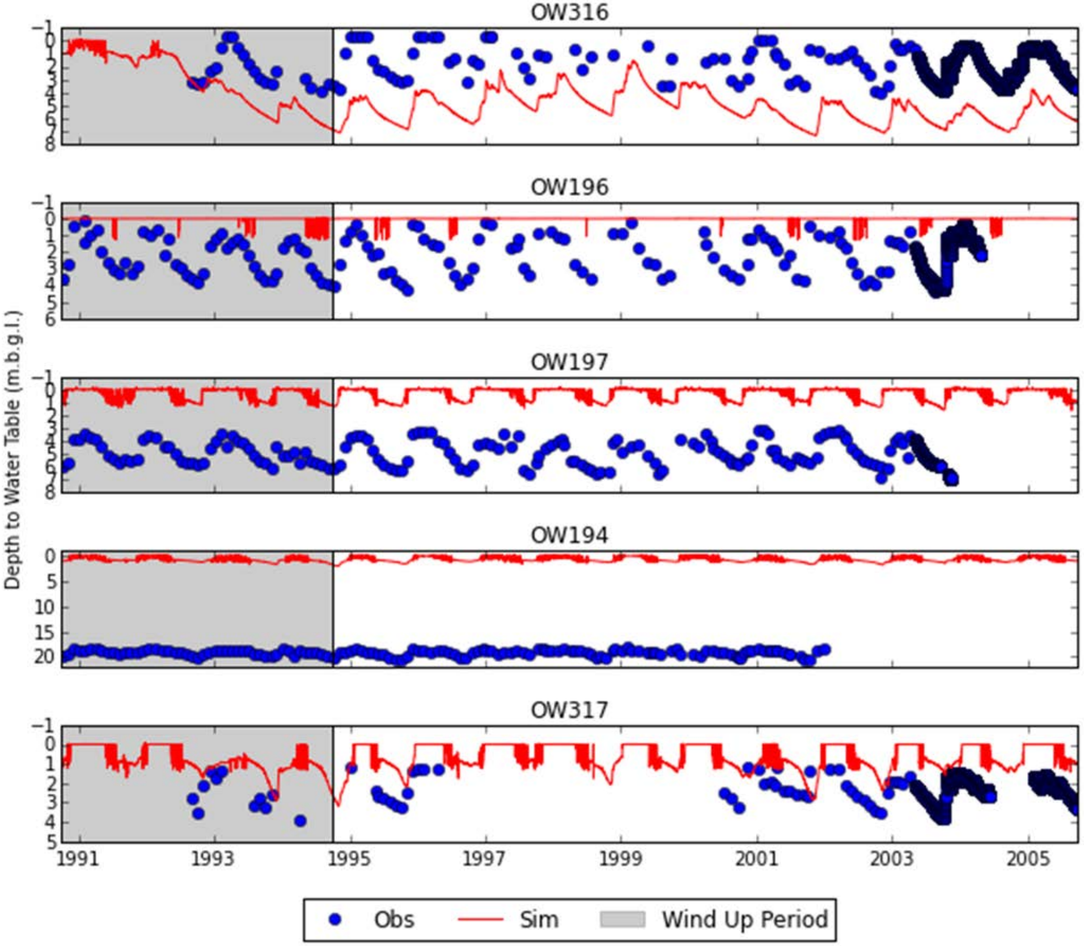
Model Calibration

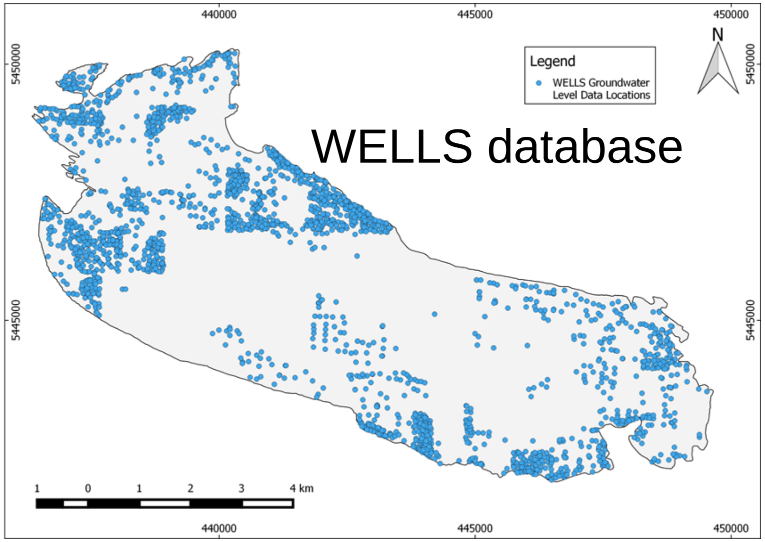


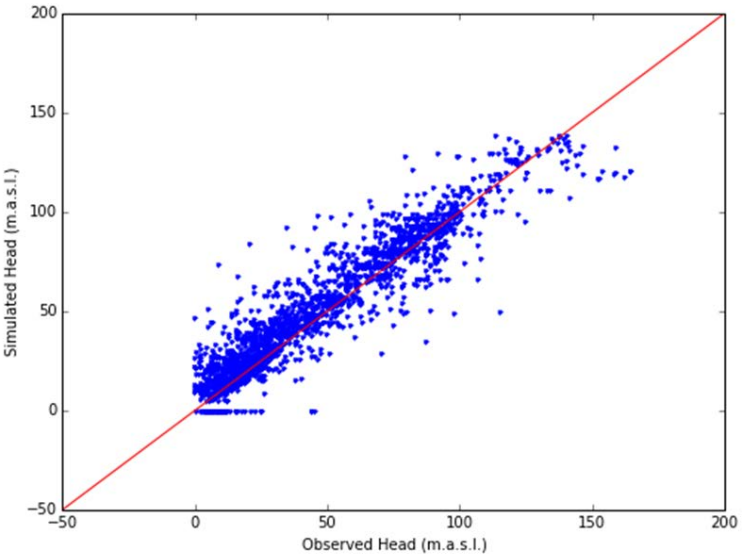


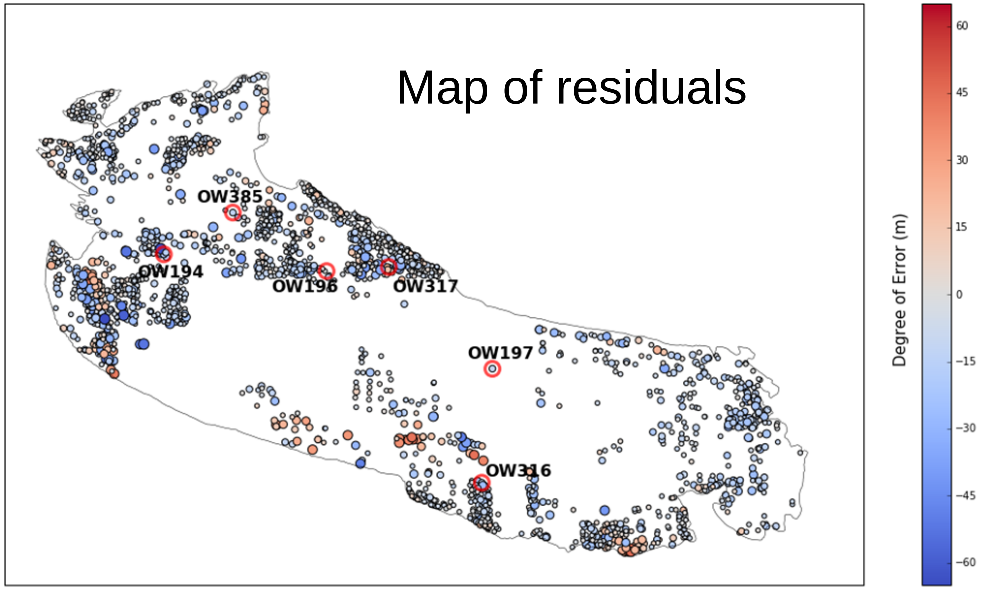
Two calibration phases:

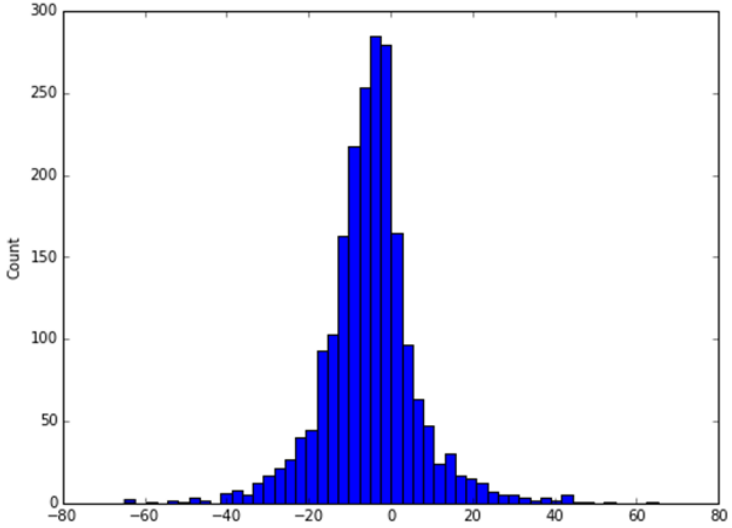
1) Transient groundwater levels were simulated and compared to the BC Obs. Wells
2) Static groundwater levels from the WELLS database were compared to average simulated groundwater levels

Burgess (M.Sc. In progress)


WELLS database



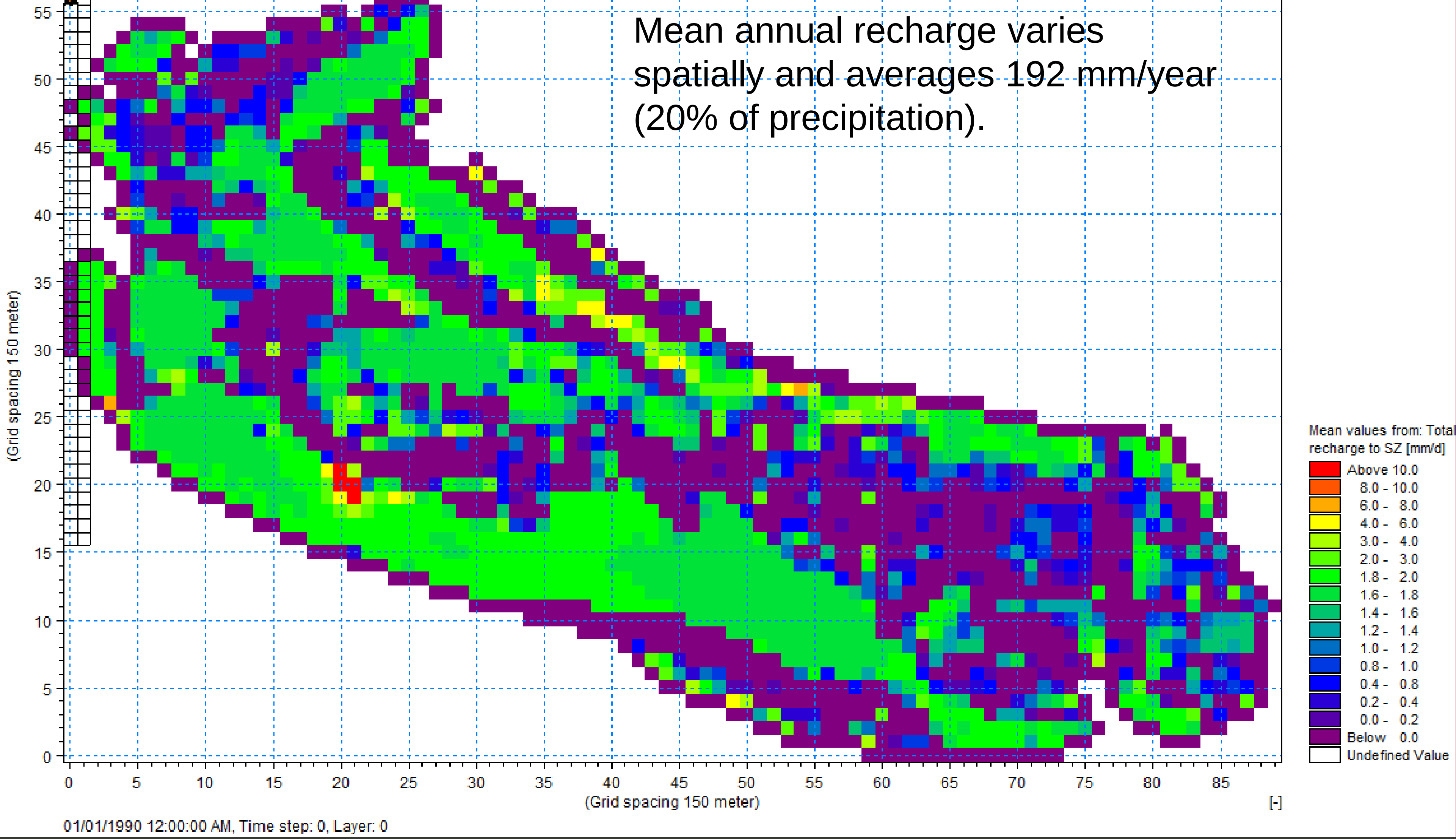

Map of residuals



Model Calibration

Burgess (M.Sc. In progress)

Recharge Results



01/01/1990 12:00:00 AM, Time step: 0, Layer: 0

Mean annual recharge varies spatially and averages 192 mm/year (20% of precipitation).

Burgess (M.Sc. In progress)

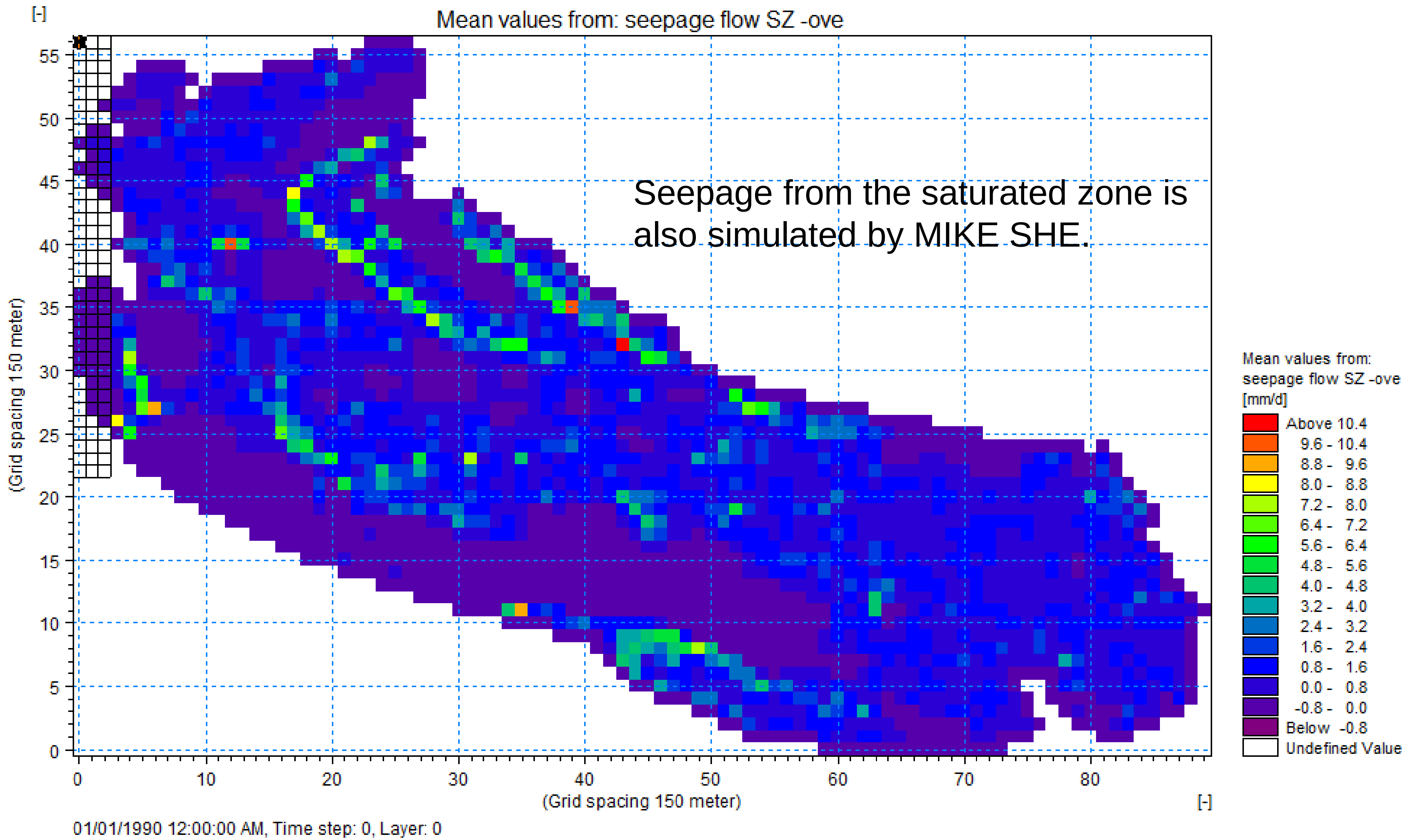
2 years (Oct 1, 1996 to Sept 30, 1998)

Year 1 - 1252 mm of precip; year 2 - 790 mm of precip

Recharge Dynamics

Burgess (M.Sc. In progress)

Seepage Locations



Seepage from the saturated zone is also simulated by MIKE SHE.

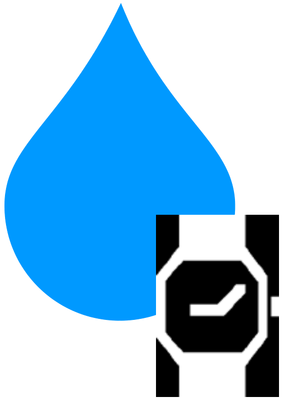
Burgess (M.Sc. In progress)

Climate Influences on Recharge

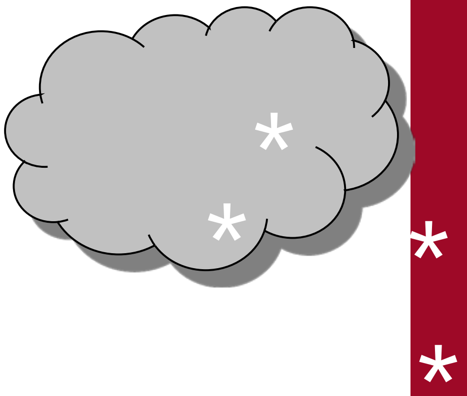
Changes to recharge rates are determined by spatial and temporal changes in climatic factors and their interactions with surface and shallow subsurface conditions.

Key climatic factors in determining recharge:

Variation in amount



Timing



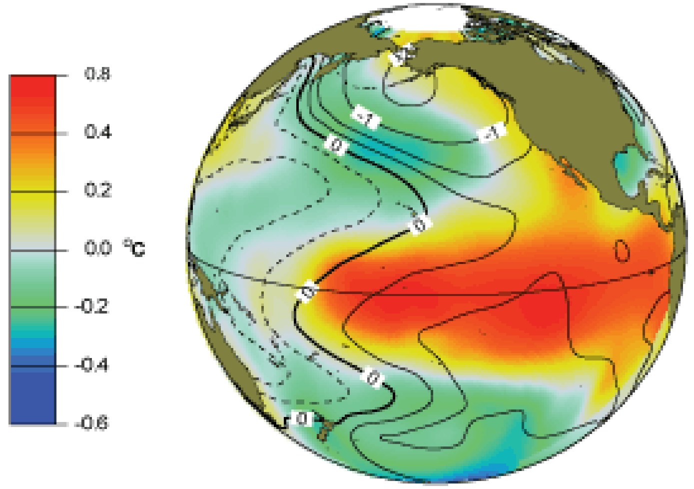
Form

More recharge?
Not necessarily uniform

More perhaps, but
all at once?

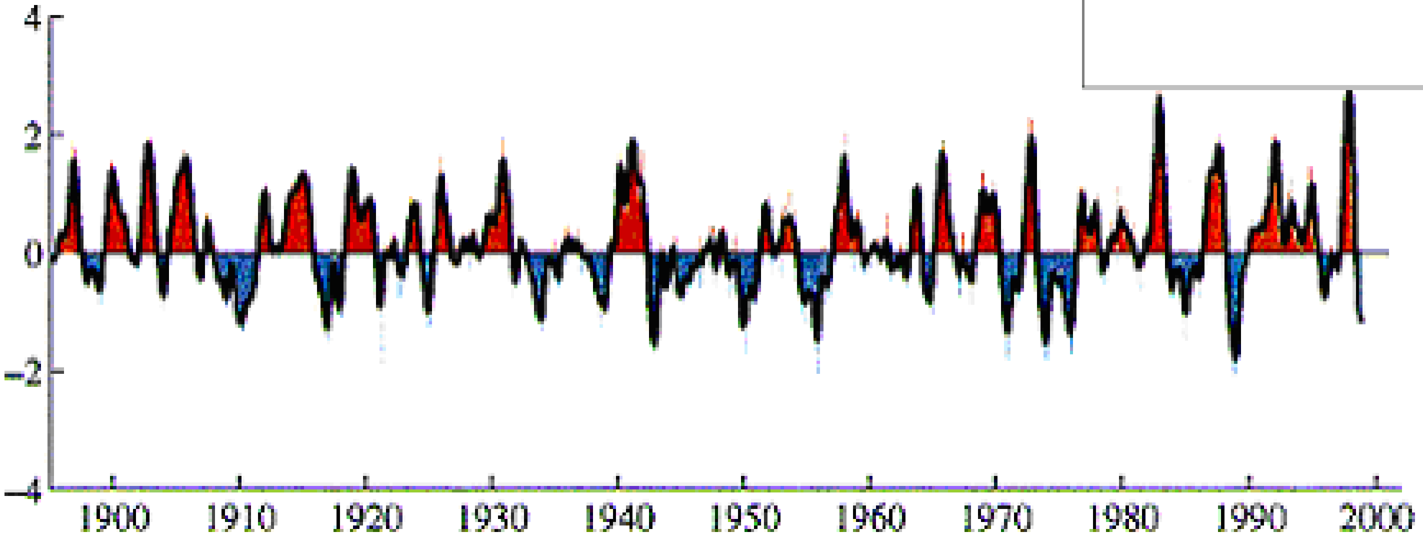
Snowmelt recharge is
dominant in most parts
of Canada and Northern USA

- The Pacific region is dominated by variations in precipitation over longer time scales (decades)
- These are the result of the PDO (Pacific Decadal Oscillation) and the ENSO (El Nino Southern Oscillation).

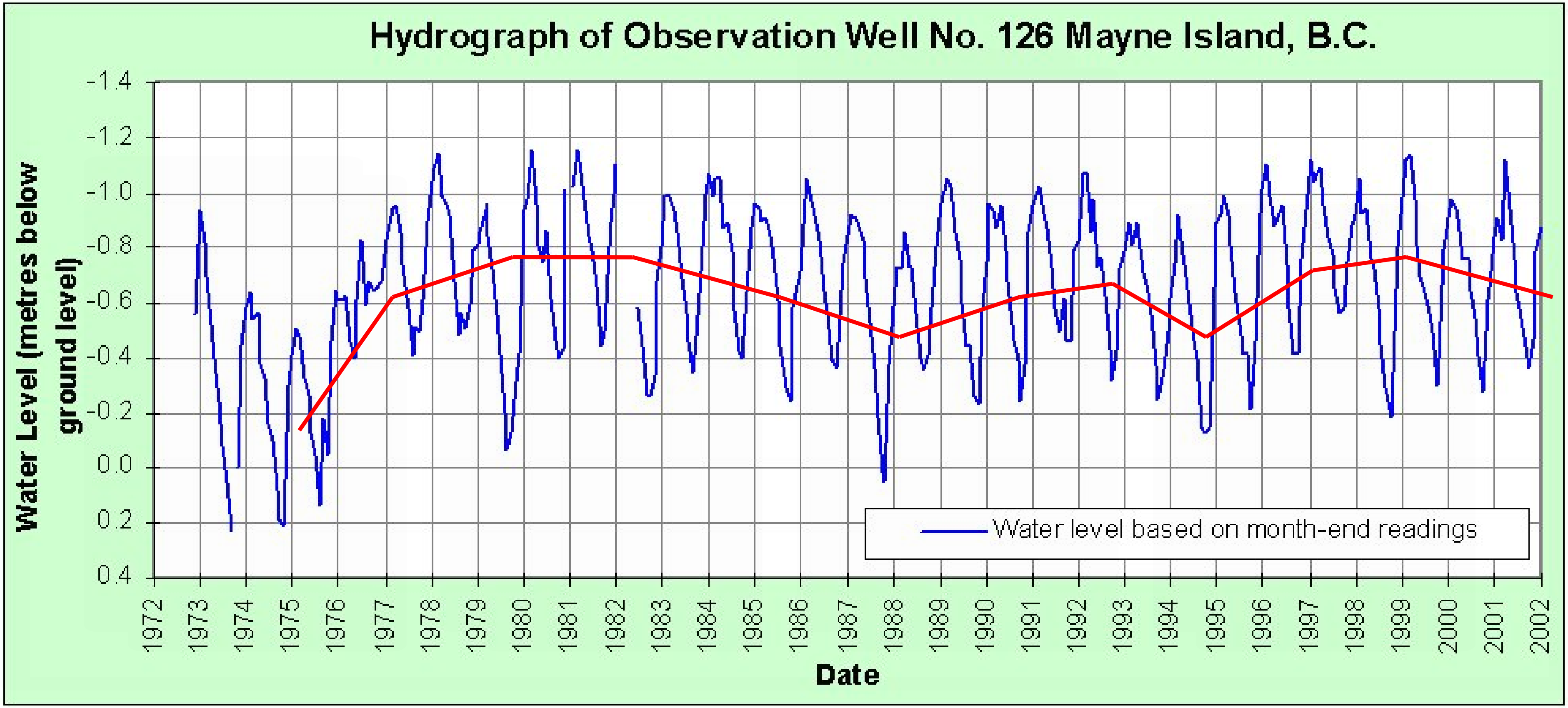


Warm Phase ENSO

Source: Climate Impacts Group, University of Washington



Climate Variations

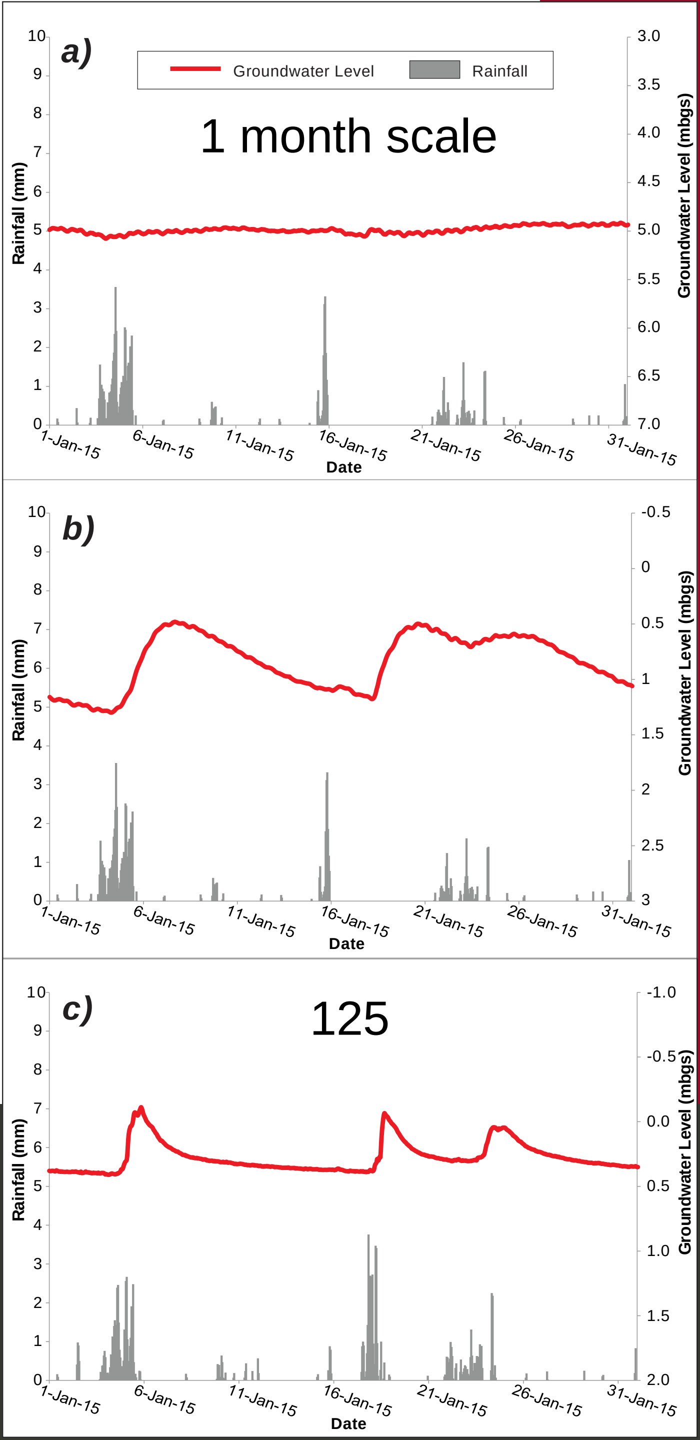


Trends in groundwater level must be examined keeping in mind these variations.

GW Hydrographs

1. We have carried out an analysis of the hourly groundwater level hydrographs for provincial observation wells in the Gulf Islands to study responses to heavy rain events.
2. Three types of groundwater level responses to rainfall were visually identified:
    - none (a)
    - damped (b)
    - Pronounced (c)
3. Cross-correlation analysis was used to show:
    - The well with the shallowest water table and no overburden (Well 125) had the strongest correlation, shortest lag time, and most distinct peak lag time.
    - The strongest correlation was observed during the summer season.

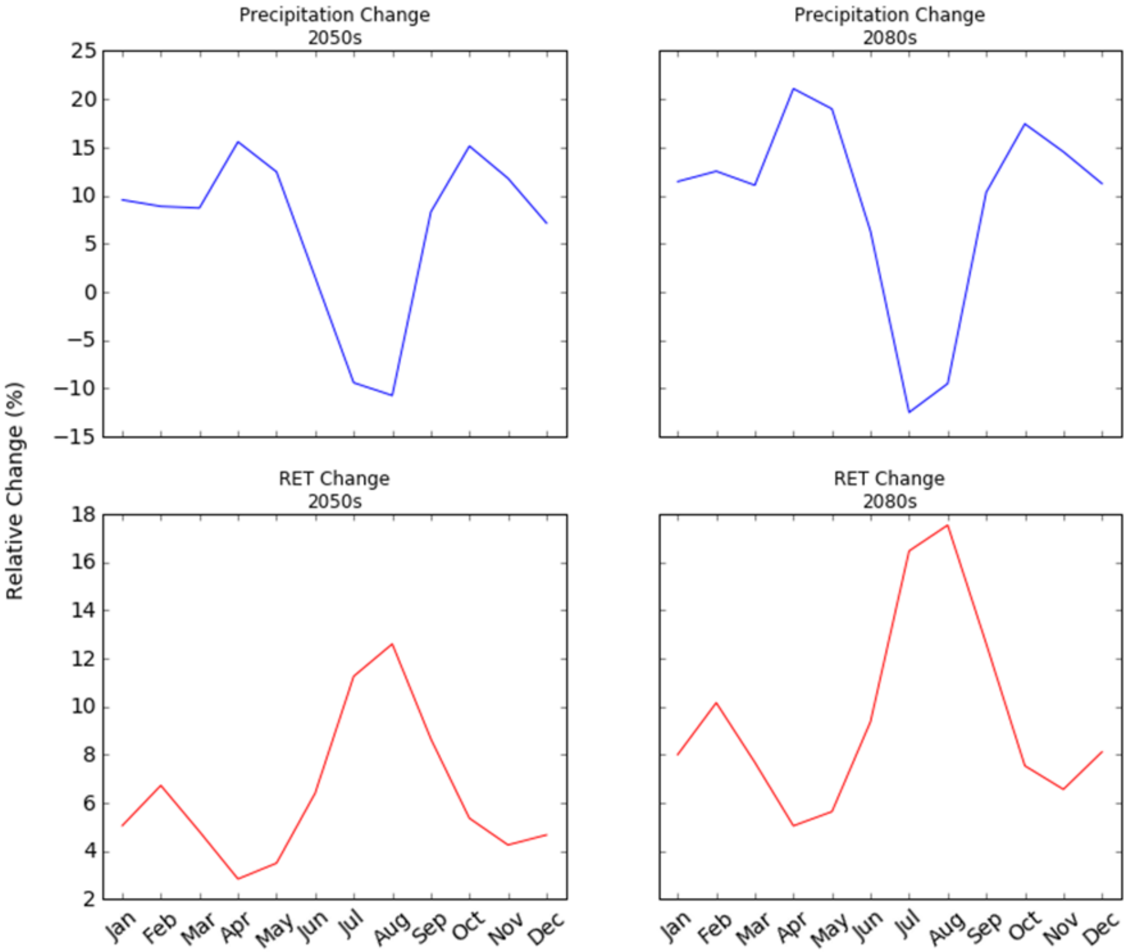
Rathay (M.Sc. in progress)



Climate Change Impacts on Recharge

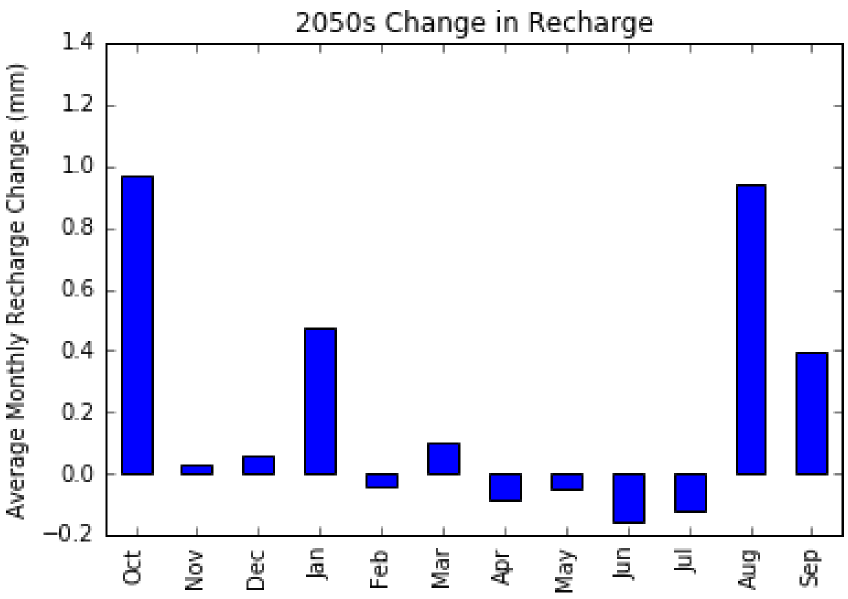
Climate change data for the 2050s and 2080s were acquired from PCIC’s Regional Analysis Tool

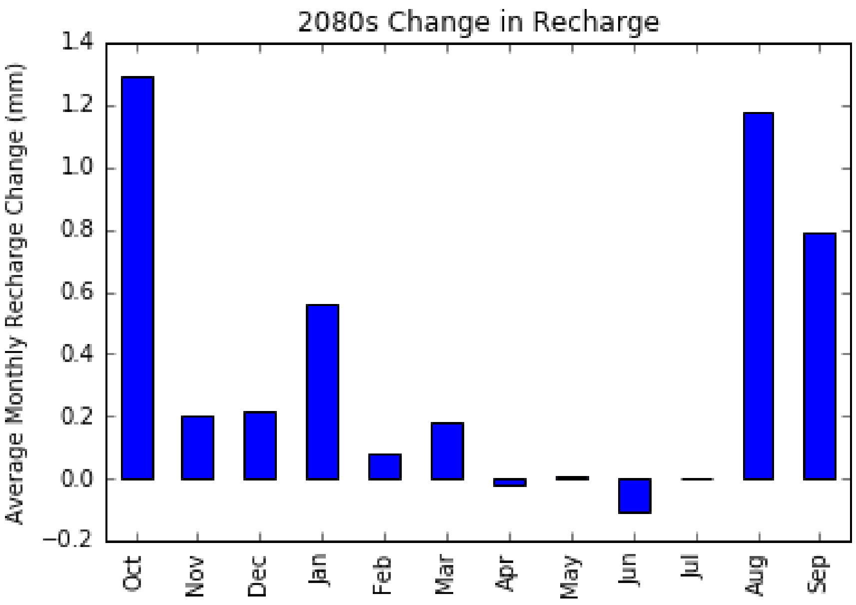
The shifts in temperature and precipitation were used to alter the climate time series used in the recharge model for Gabriola.



Burgess, MSc in prep

Recharge Changes





- An increase in recharge is simulated for the fall and winter months, with greater increases by the 2080s.
- An overall reduction in early summer recharge is simulated.

Burgess (M.Sc. In progress)

- Based on a variety of methods used over the years, annual recharge to the Gulf Islands has been estimated to be in the range of 3-60% of annual precipitation. Each method carries high uncertainty.
- Recharge cannot be estimated using 1D models with a fixed water table depth, because seepage faces develop as the water table rises, removing water from the system.
- Using a coupled land surface – subsurface hydrologic model (MIKE SHE), we estimate an annual average recharge of 20% of precipitation. This value remains uncertain due to uncertainties, for example, in the width of the seepage zone at the ocean (range of 10-25% of precipitation)
- Recharge varies spatially from <0.1 to ~6 mm/day, with an average of ~0.49 mm/day.
- Recharge varies with climate cycles (PDO and ENSO cycles)
- Recharge to the Gulf Islands will likely not change by very much on an annual basis, but summer recharge will likely lessen and winter recharge possibly increase, although the groundwater levels are already high in winter so the aquifer storage may be at capacity.

Conclusions

Thank You

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