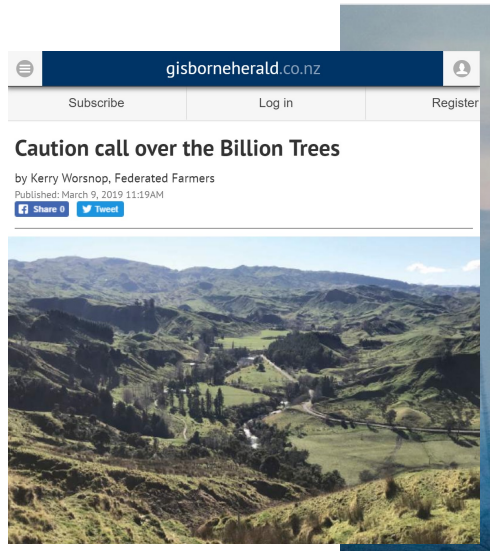
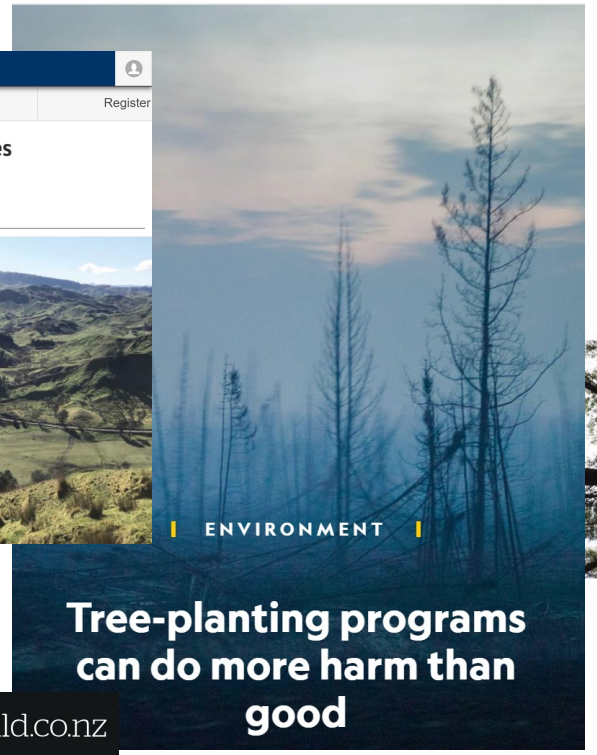
Forest Flows: Integration of Terrestrial, Remote Sensing and Airborne P-Band SAR Data for Identifying & Quantifying the Drivers of Forest Hydrological Processes across Different Scales

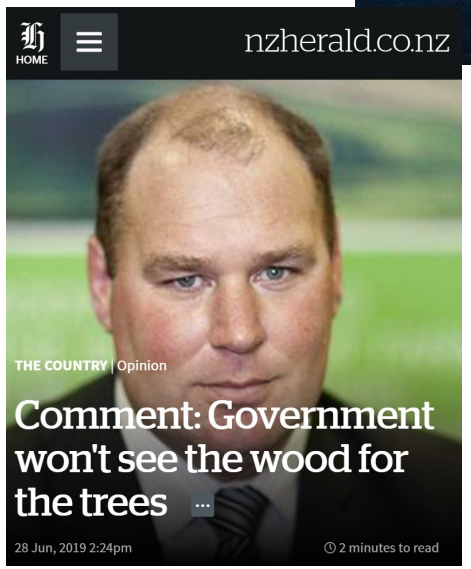
Dean F. Meason, Serajis Salekin, Priscilla Lad, Jennifer Owens, Yi Zhang, Grace Villamor, Don White, Jianming Xue, Hongfen Zhu, Bruce Dudley, James Griffins, John-Mark Woolley, Alec Dempster, MS Srinivasan, Channa Rajanayaka, Albert Bifet, Guilherme Cassales, Delwyn Moller, Robert Schafer, Mahta Moghaddam, Mia Zhao, Jake Diamond, Brian Strahm, Kevin McGuire, Yinphan Tsang, and Amanda Matson

Trees, water use, and forest water yield

- Increasing concern with water availability & quality
- Concern about impact of large-scale forest plantings
- Increasing questions on how much water *Pinus radiata* and other tree species use and downstream impacts on water supply
- Little research in forest hydrology over the last 40 years
- Lack of data and information
- Information “black hole” being filled with commentary







Forest Flows Programme (2019-2024): from 2D “black box” to 3D drivers approach

Three overall objectives:

- Planted trees water use – focus on radiata pine
- Planted forest catchments water storage
- Planted forest catchments water release

$$\Delta S = P - Q - ET + \varepsilon$$

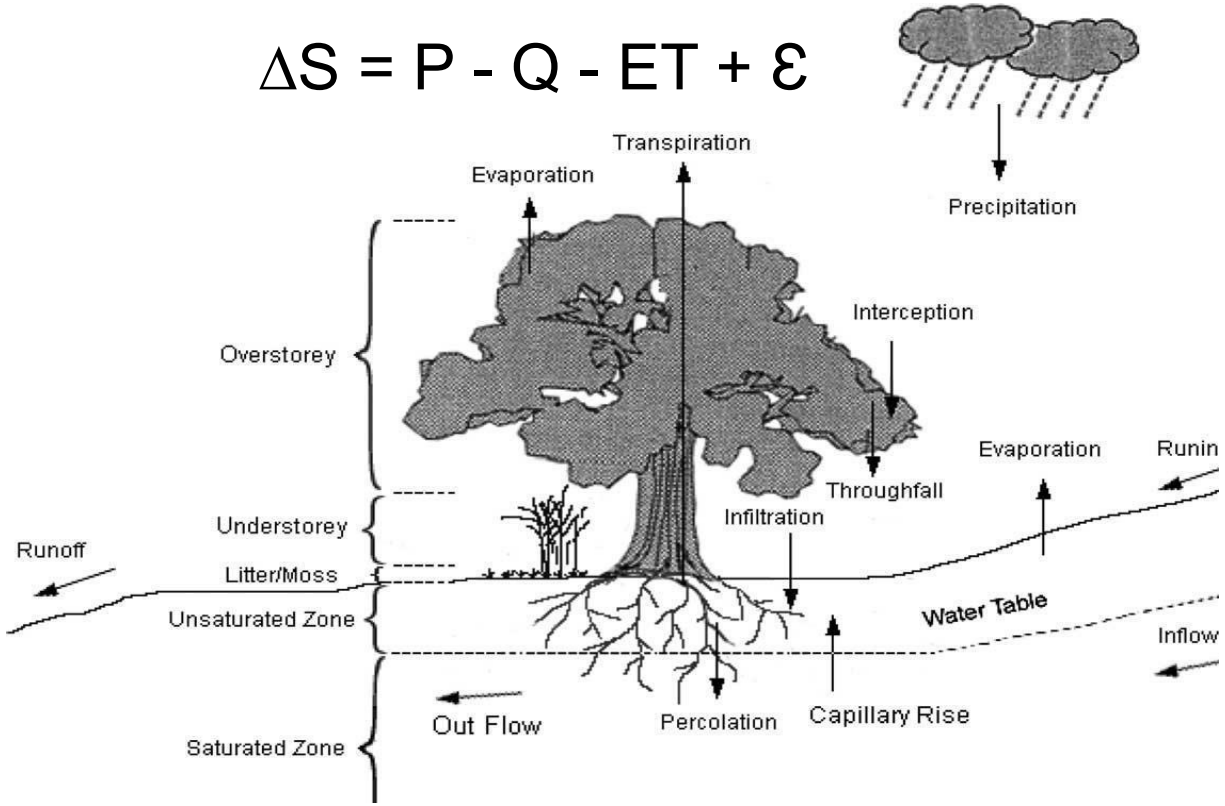
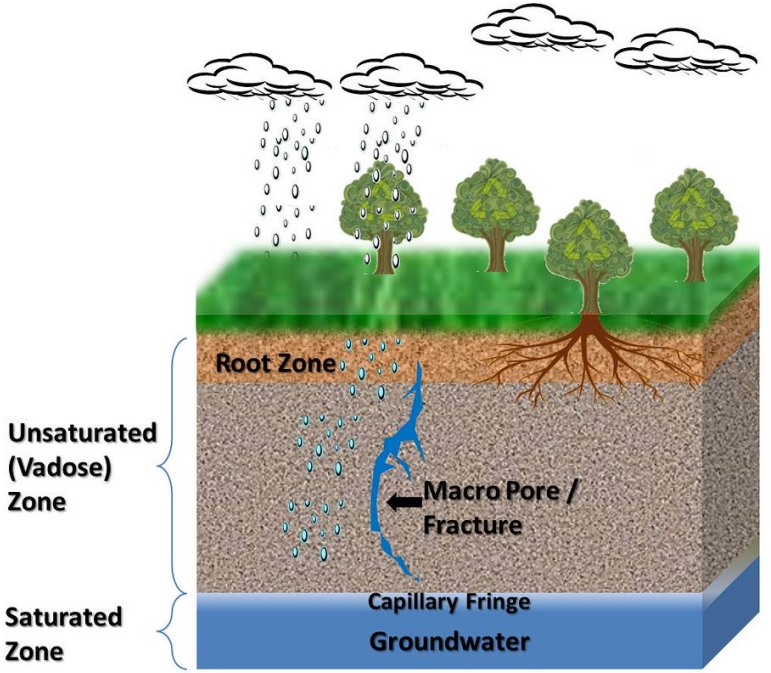
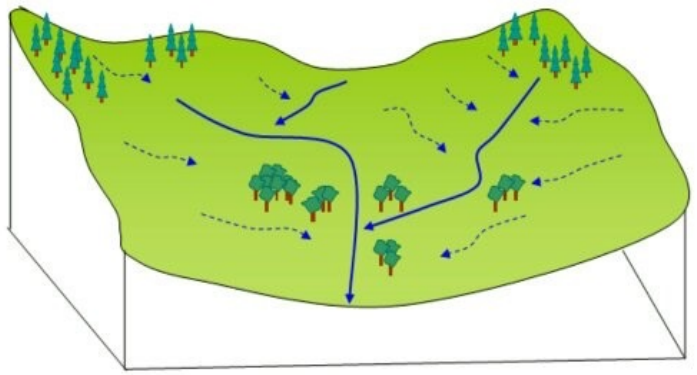


Figure 1 Hydrological processes at the forest scale (Chen et al., 2005)



Texas Water Resources Institute: https://www.flickr.com/photos/twri/8169729760/



A catchment area.

https://qph.ec.quoracdn.net/main-qimg-304b34b4131e6a4250f92d8c482e61a2

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Forest Flows programme – integrated measurements with terrestrial and remote sensing data

Satellite

- Soil moisture
- Tree canopy water stress

Airborne

- SlimSAR L- & P-band radar
- Tree canopy water stress

Above Ground

- Weather station
- Rainfall
- Throughfall
- Tree growth & water use
- Water age
- Streamflow

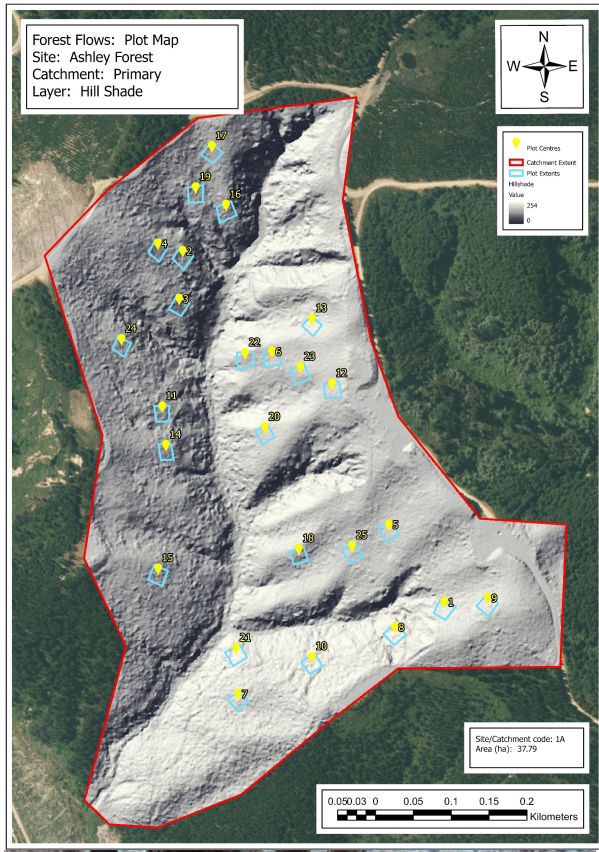
Below Ground

- Soil moisture
- Groundwater
- Water age
- Soil texture & depth
- Ground penetrating radar

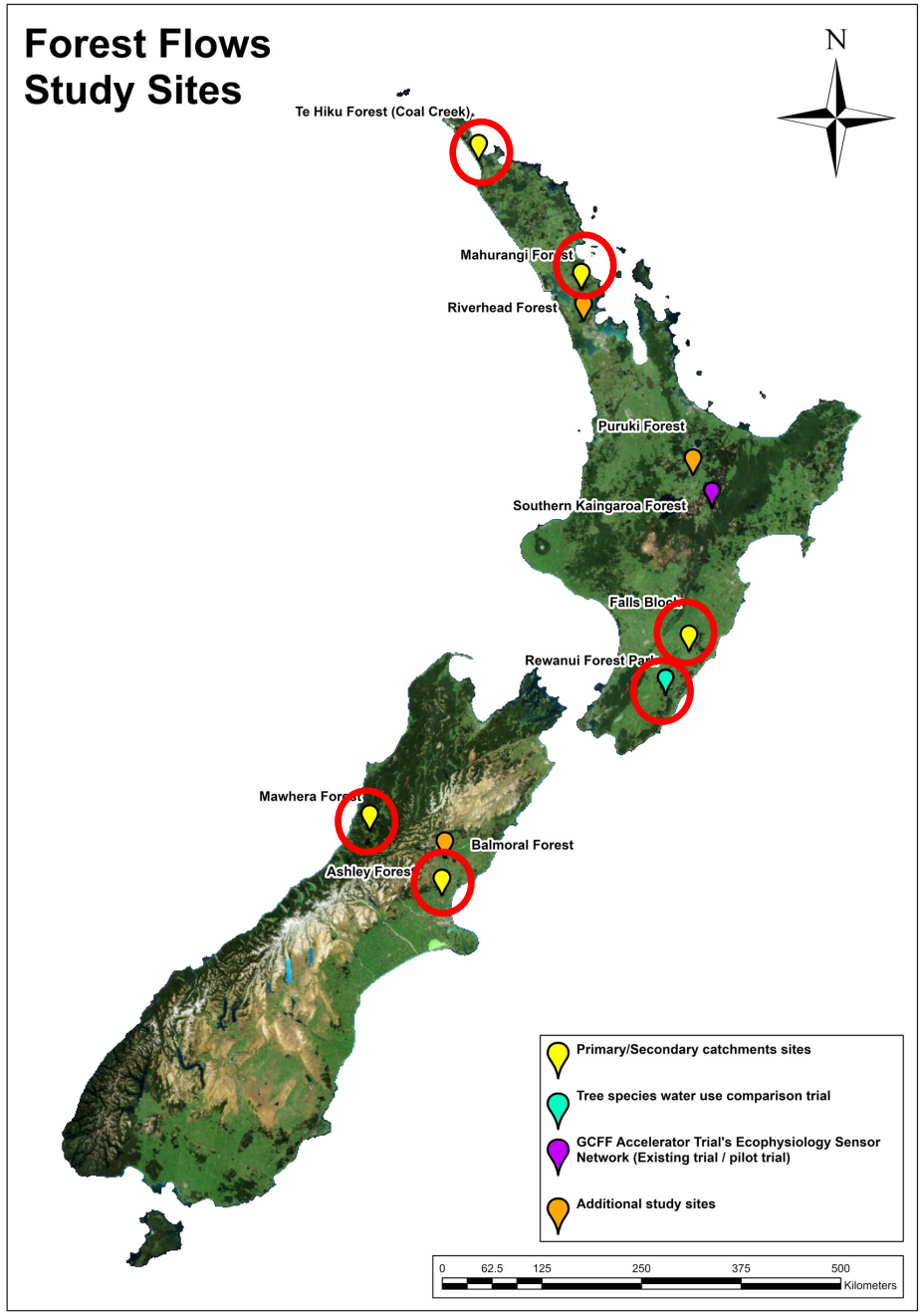
1,717
instruments across seven sites

360,000
observations a day

130 million
observations over the last year



Forest Flows sensor network data flow overview



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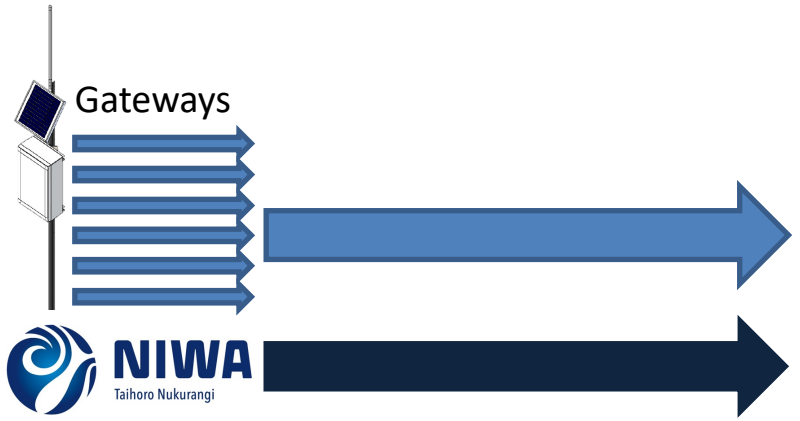
Near Real Time, Environmental Big Data from Wireless Meshed Networks

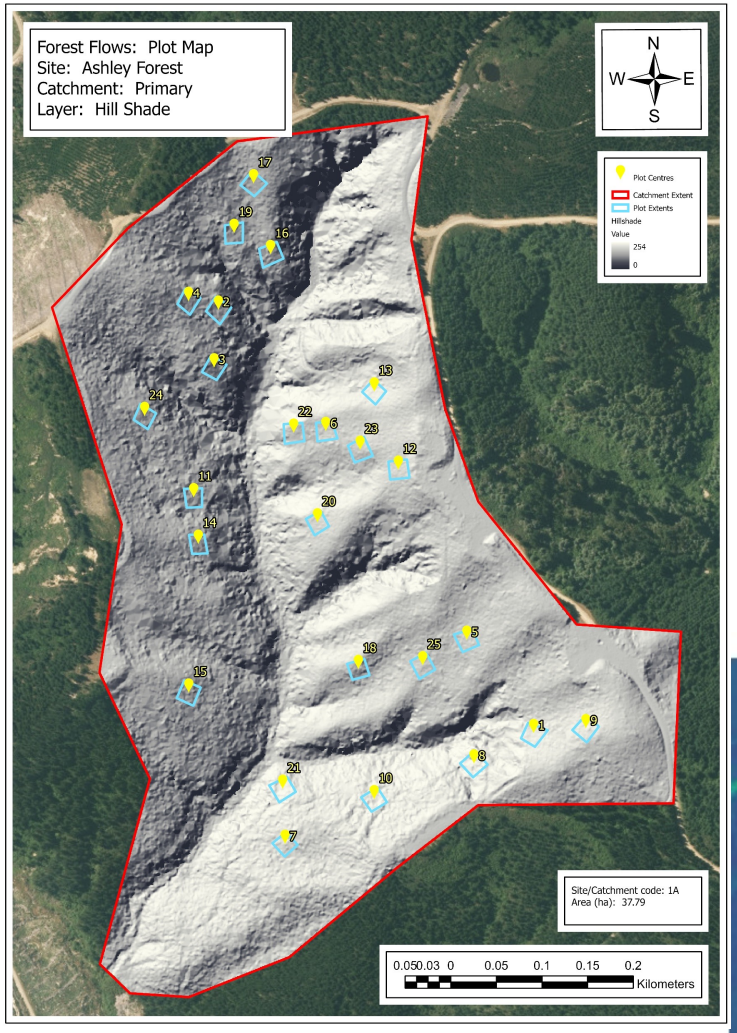


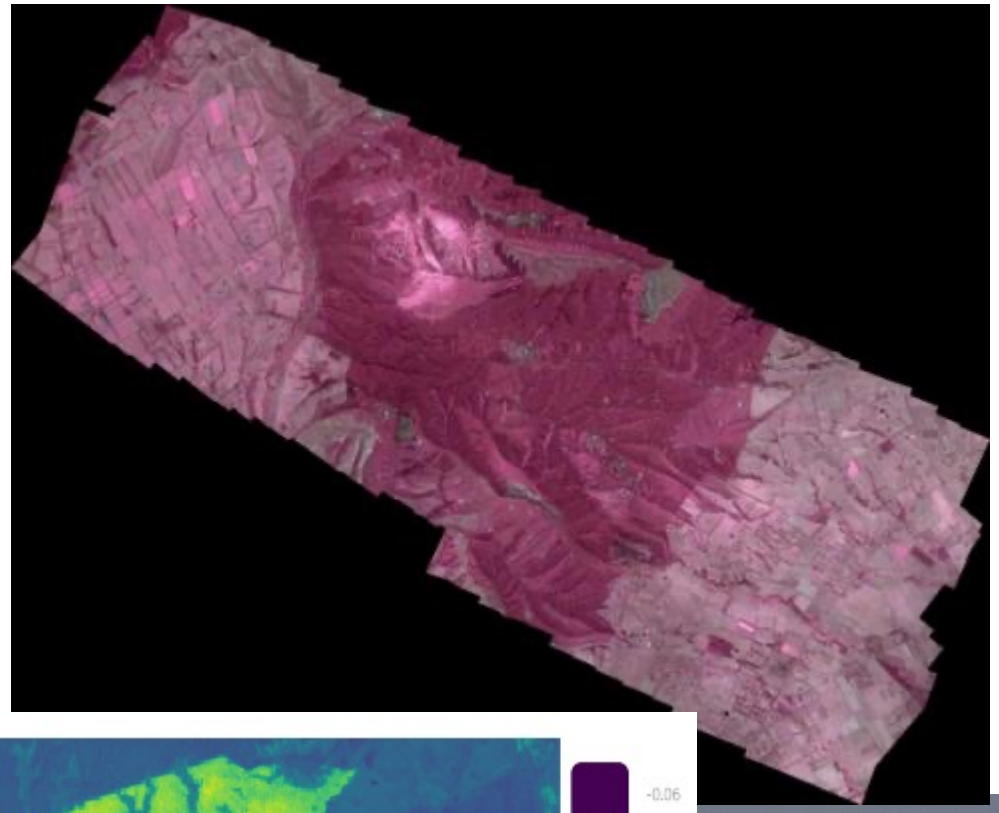
Primary Research Catchments (yellow pins)

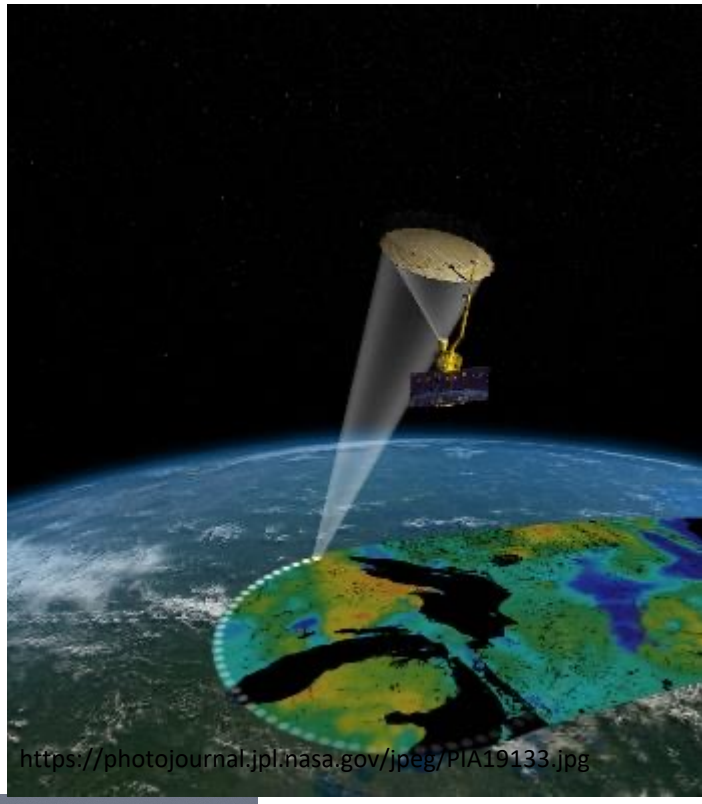
Site	Annual ppt (mm)	Area (ha)
Te Hiku	1,200	1,800
Mahurangi	1,600	37
Titoki	1,200	61
Ashley	800	38
Mawhera	3,000	102

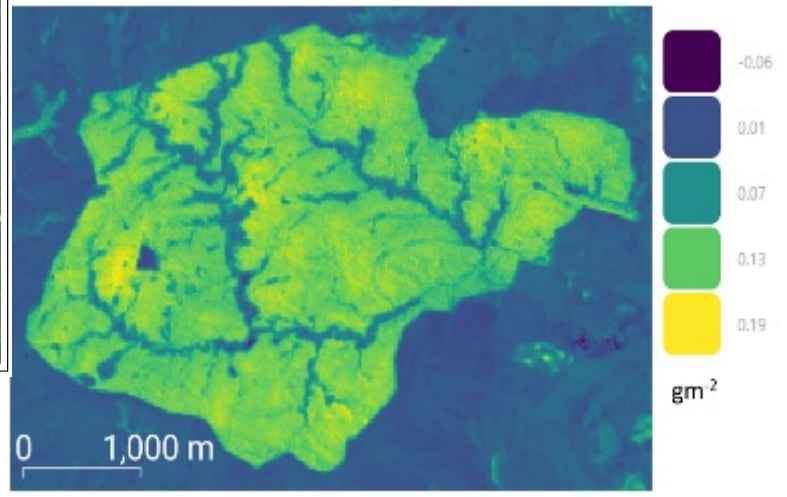
Telemetry data from 6 sites
1,717 instruments
Measurements 5 min intervals
360,000 observations per 24 hrs
>130 million data points over the last year

Forest Flows - Remote sensing for scaling from plot, to catchment, to forest









https://upload.wikimedia.org/wikipedia/commons/a/ae/Cessna_172S_Skyhawk_SP%2C_Private_JP6817606.jpg

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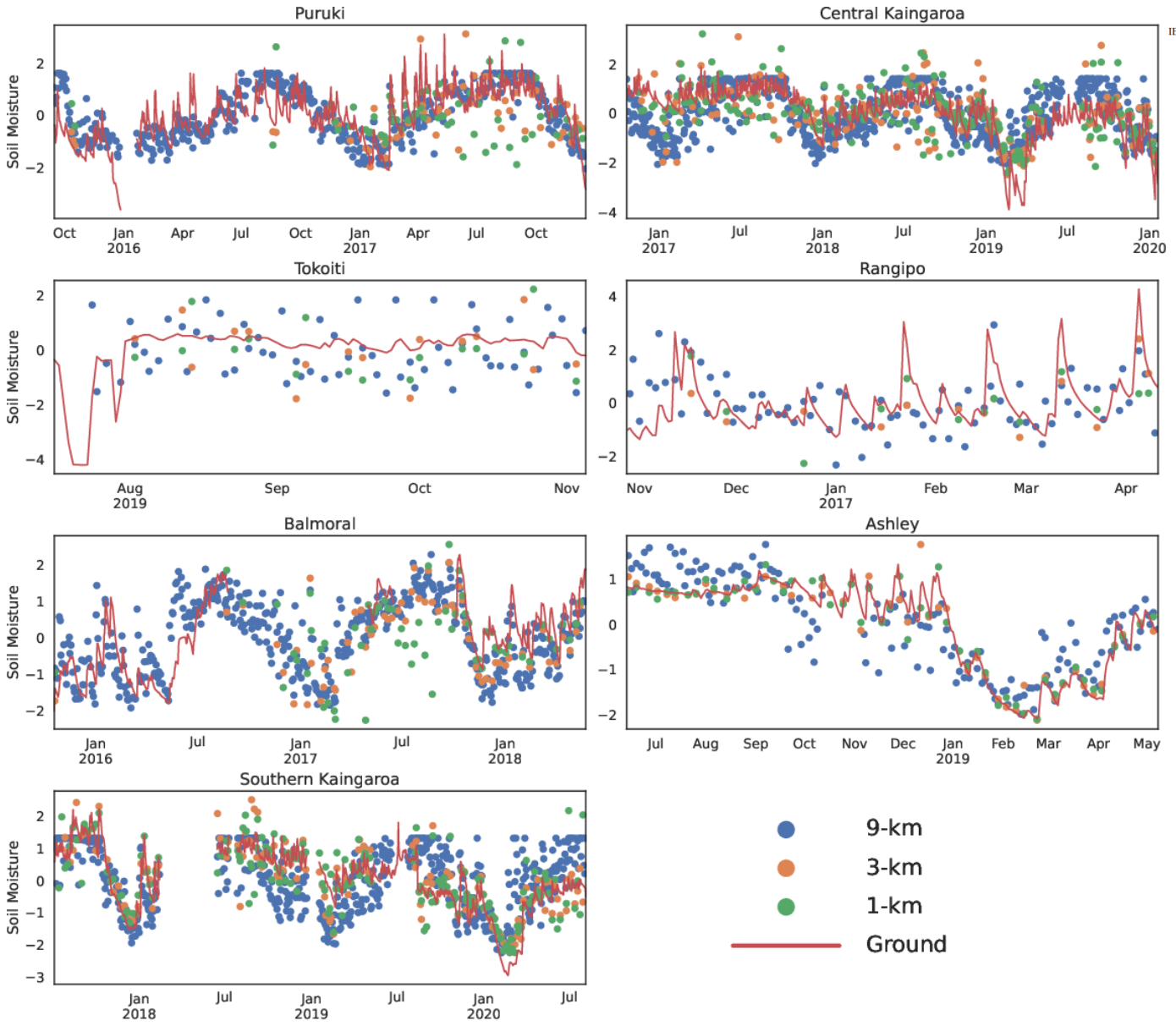
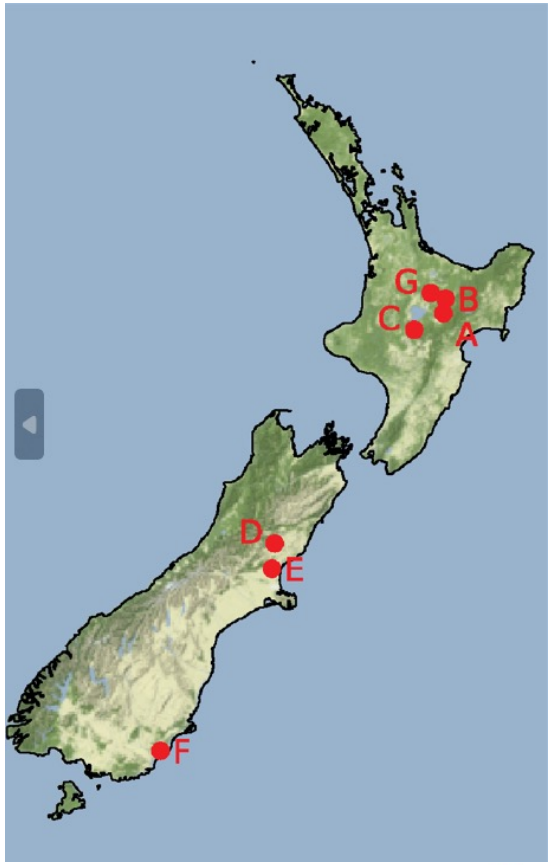
SMAP validation in forest soils



IEEE GEOSCIENCE AND REMOTE SENSING LETTERS, VOL. 19, 2022 2505805

Evaluation of Multiscale SMAP Soil Moisture Products in Forested Environments

Konstantinos M. Andreadis, Dean F. Meason, Barbara Höck, Priscilla Lad, and Narendra Das, *Member, IEEE*



Candleford

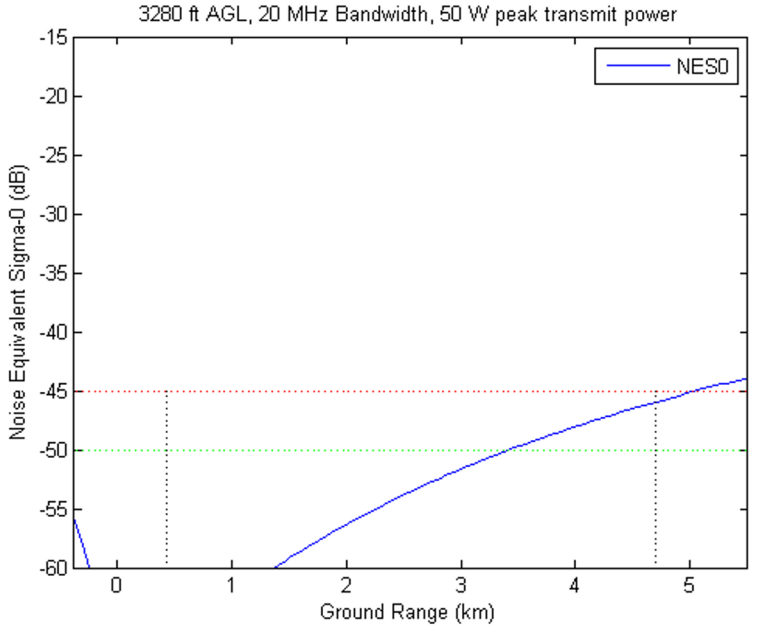
UMassAmherst

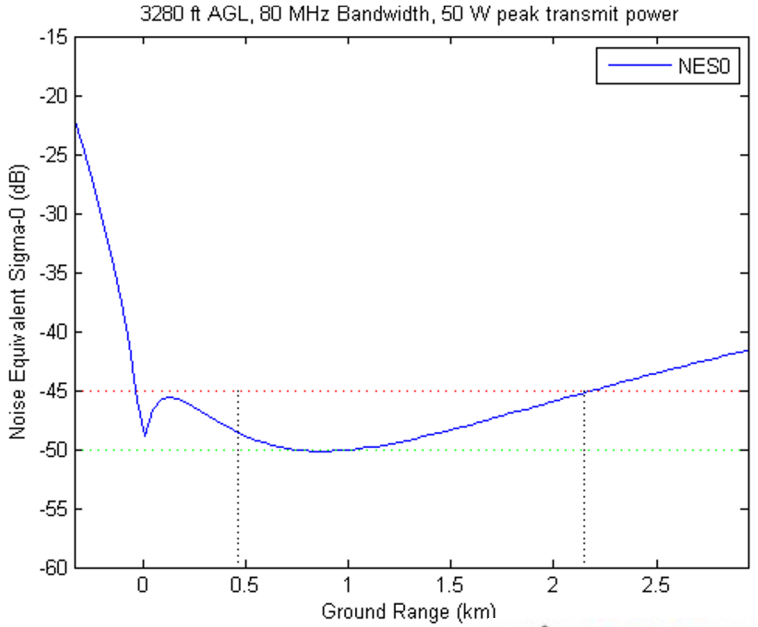
SlimSAR L- & P-Band radar

- Leased from Artemis, USA
- Campaign & radar modifications by Delwyn Moller, University of Auckland, NZ
- Cal/Val work lead by Mahta Moghaddam, USC, USA

SlimSAR Specs

Band	L	P	Unit
Centre	1255	430	MHz
Bandwidth	80	20	MHz
Max Tx Power	50	50	W
Resolution	2.5	10	m
swath@1000m AGL	1.6	2.0	km
Polarization	Quad	Quad	





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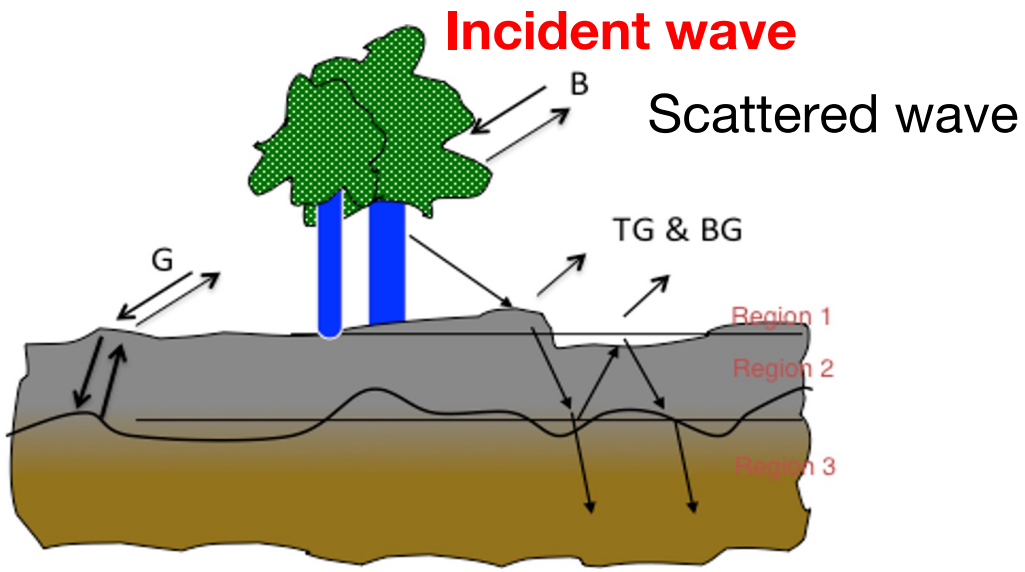
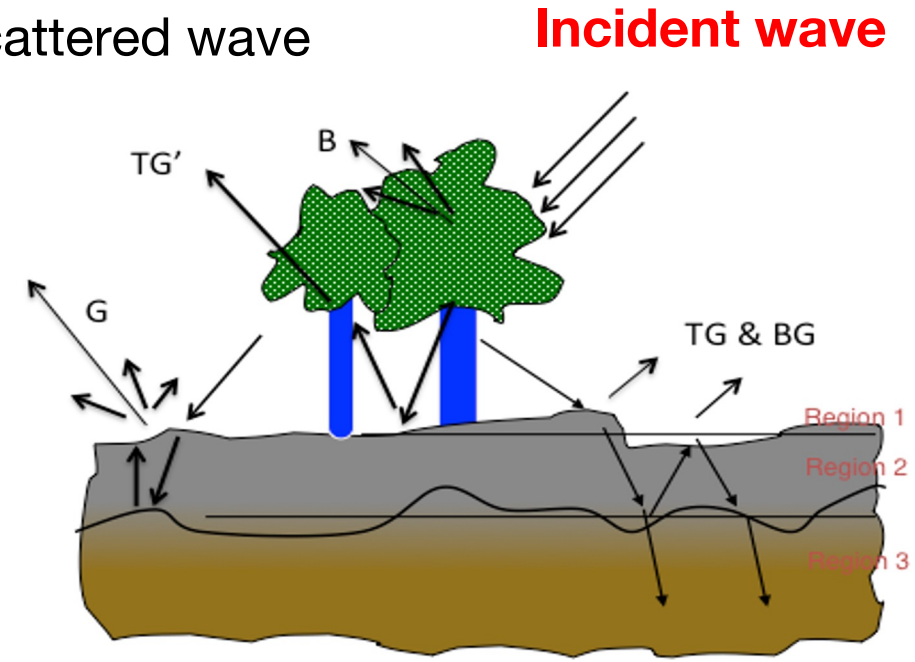
SlimSAR Background: Monostatic and Bistatic Radar Signal Paths

- Same types of scattering mechanisms are involved in both cases
- Example shows signal paths for vegetated ground: direct ground, direct branch volume, branch-ground, trunk-ground



- If frequency is low enough, scattering from ground includes scattering subsurface layers and their dielectric profiles



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MiXIL Microwave Systems, Sensors and Imaging Lab

SlimSAR L- and P-Band radar

- Flying ex Wanaka on Cessna 172
- Radar and IMU all on single plate mounted in cargo hold
- Door replaced by radar “transparent” window
- Operator sits in back. Laptop for control/communication
- Local calibration site established
- Campaigns every spring and late summer/early autumn

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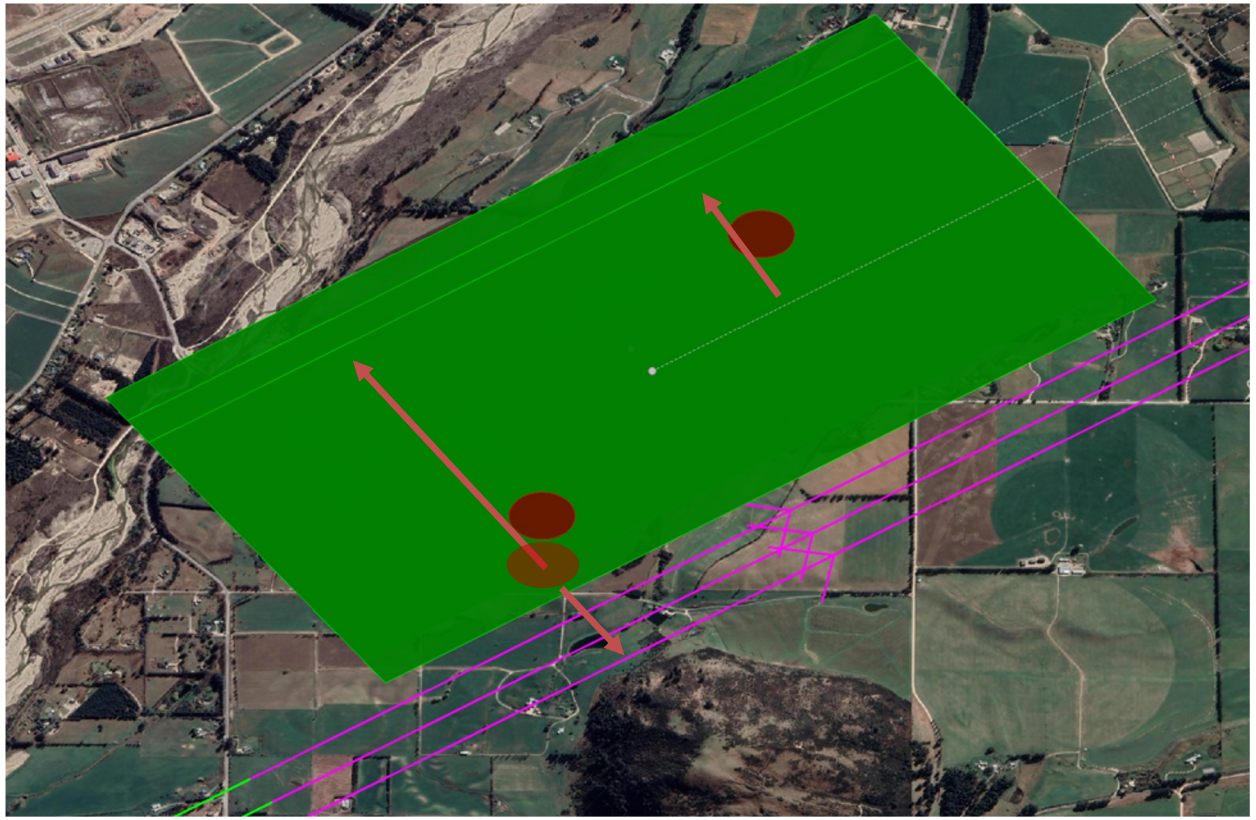
SlimSAR: Calibration targets

- Three corner reflectors (2.5m interior dimension) fabricated and deployed local to Wanaka
- Since dimension is “small” at P-band radar cross section was solved for at USC (Prof Sideris)



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SlimSAR: Forest Flows Strategy

- Forest Flows used a similar retrieval strategy to AIRMOSS for estimating soil moisture under vegetation canopies
    - Advantage of Forest Flows: dual frequency
    - Soil moisture primary target for Forest Flows, however, raw data collected of the above ground biomass

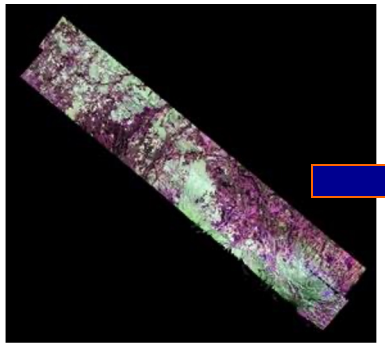
- The algorithms can be made more sophisticated by including ***topography*** underneath the canopy

- Radar imagery need to be calibrated prior to applying retrieval algorithms
    - Normalised radar cross-section/$\sigma_{pq}(\theta_i)$ primary input to retrieval
        - Requires absolute calibration – goal 0.5dB

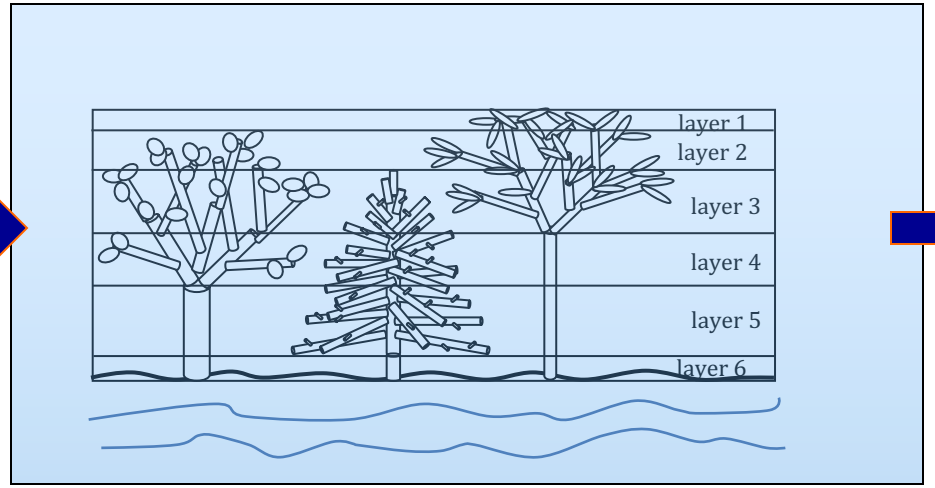
- SlimSAR has a near-realtime SAR processor that generates geo-referenced complex compressed images
    - Note that system is both L- and P-band providing additional measurements for the inversions
        - L-band used for satellite-based SM products – relatively mature retrievals for surface SM
    - Noise equivalent σ0 requirement -50dB P-band, -45 dB L-band
    - Custom post-processing developed to generate calibrated products for geophysical retrievals

SlimSAR: Soil moisture retrieval approach

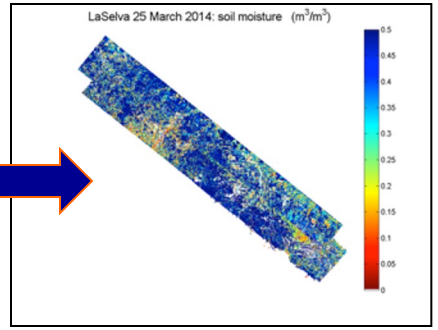
Radar backscattering cross section image



Numerical EM scattering model



Soil moisture

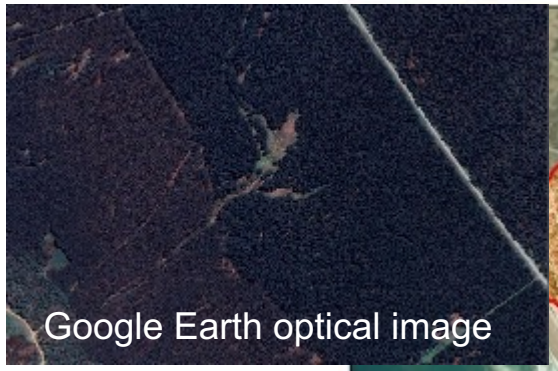


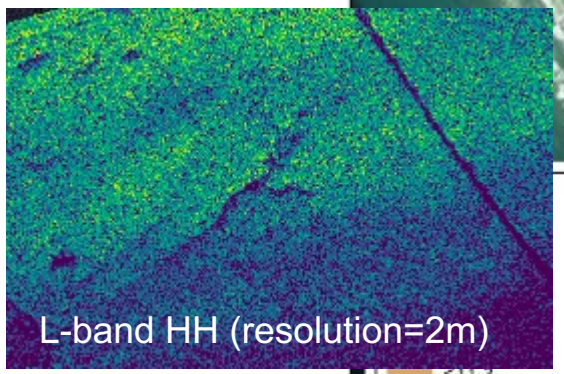
- We use an inversion algorithm to find the best set of numerical radar scattering model parameters that matches radar measurements
- Solution uses a global optimization to minimize a cost function
- There are too many unknowns and only 3 measurements per frequency per radar image pixel: use simplifying assumptions to reduce # of unknowns

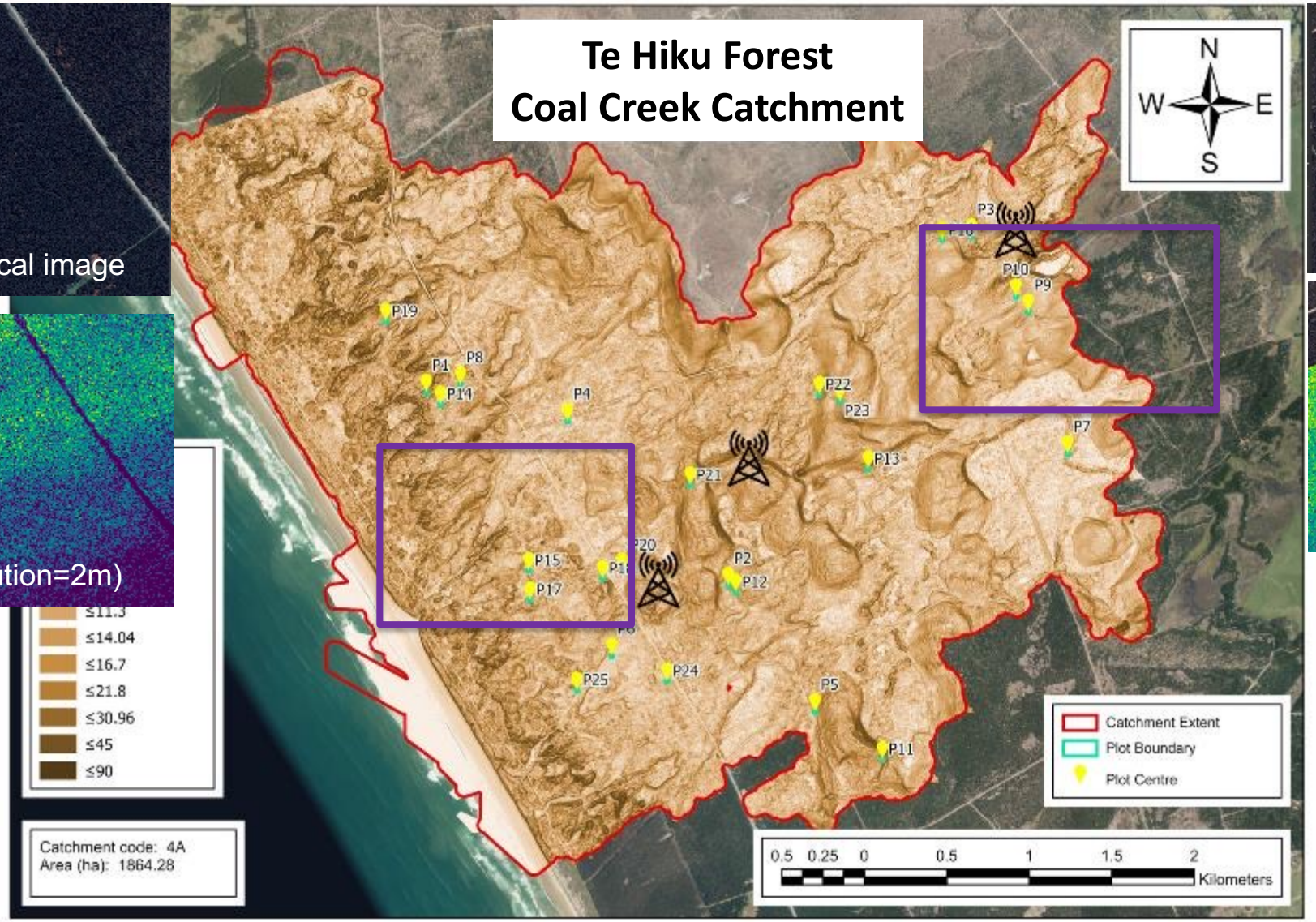
Campaign summary	Site Factors	Dominant Tree Species	Substory Present?	Understory Present?	Campaign 1	Campaign 2	Campaign 3
Corner Reflectors	Flat		N/A	N/A	P&L Nominal+	P&L Nominal+	P&L Nominal+
Ashley Forest, South Island: Catchment 3	Moderate topography	*Pinus radiata*	No	Yes – some locations	P&L Nominal+	P & L nominal+	P & L nominal+
Mawhera Forest, South Island: Catchment 5	Moderate to high topography	*Pinus radiata*	Yes - common	Yes – dense	P&L Nominal+	L-only+	P & L nominal+
Mahurangi Forest, North Island: Catchment 1	Moderate to high topography	*Pinus radiata*	Yes	Yes – moderate density	Not collected - Weather	P nominal+ L-band data+ drops*	P & L nominal+
Te Hiku Forest, North Island: Coal Creek	Low topography w dunes	*Pinus radiata*	No	No	P&L Nominal+	P nominal+ L-band data + drops*	P & L nominal+
Titoki Forest, Falls Block, North Island: Catchment 4	Rolling topography	*Pinus radiata*	No	No	Not regular flight lines due to flight safety	P nominal L-band data drops*+	P & L nominal+
Balmoral Forest, South Island (i.e. the flat forest near Ashley Forest).	Flat Analog to the Ashley site	*Pinus radiata*	No	No	P&L Nominal+	P & L nominal+	P & L nominal+

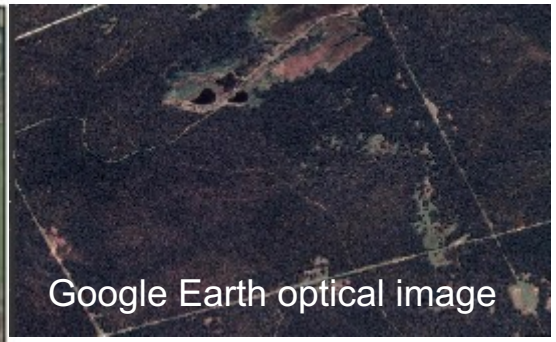
*working on a correction due to dropped pulses
+Calibration loop data delivered

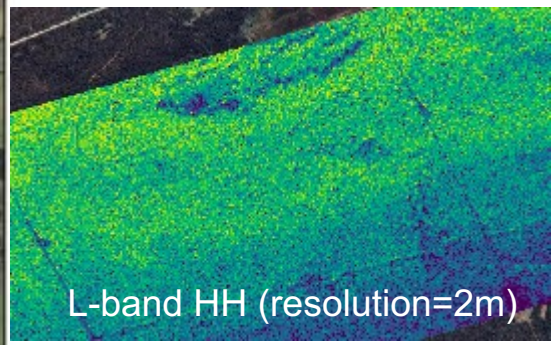
SlimSAR: L-Band Preliminary results





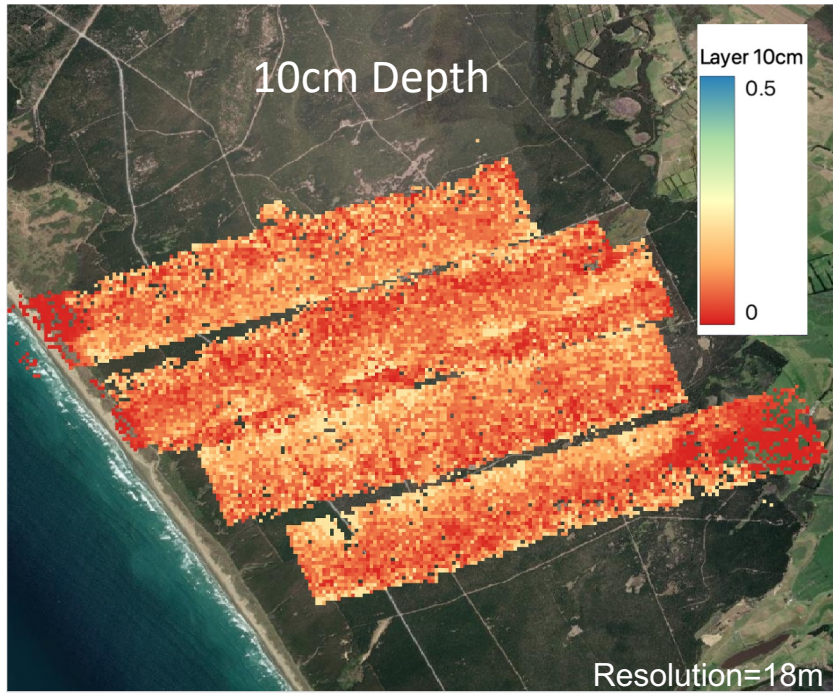


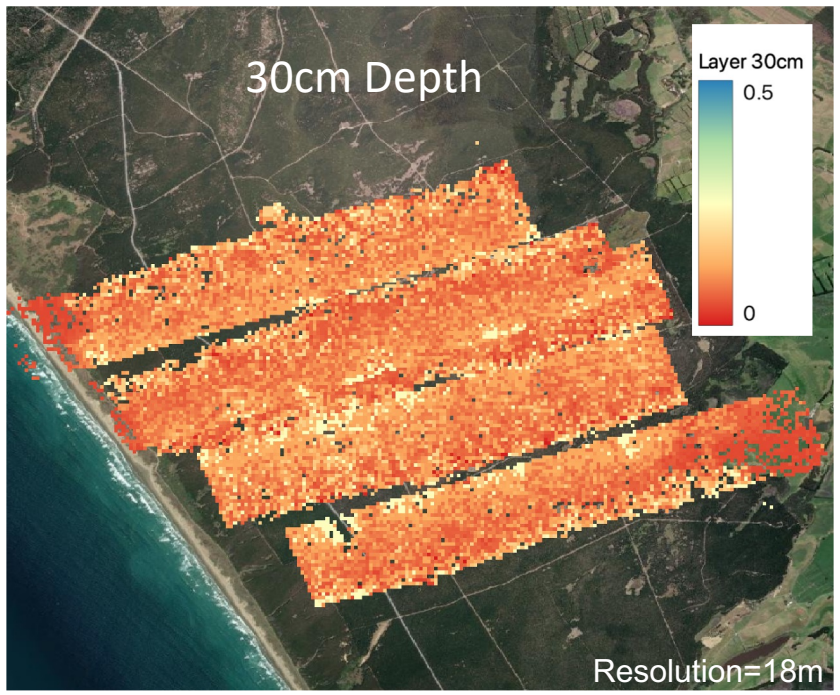


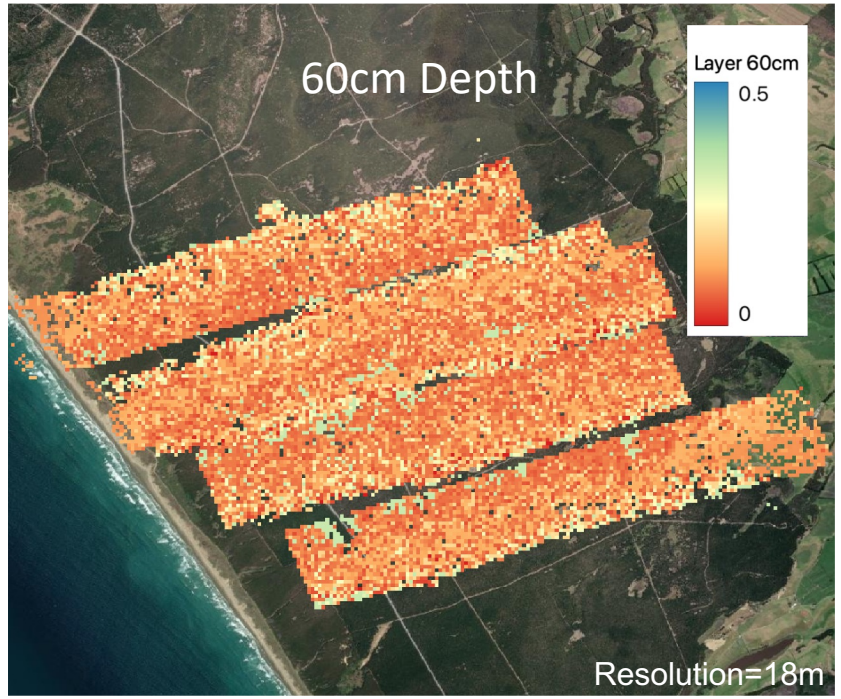


SlimSAR: P-Band preliminary results

Soil Moisture Retrieval for First Campaign: Late Summer 2022







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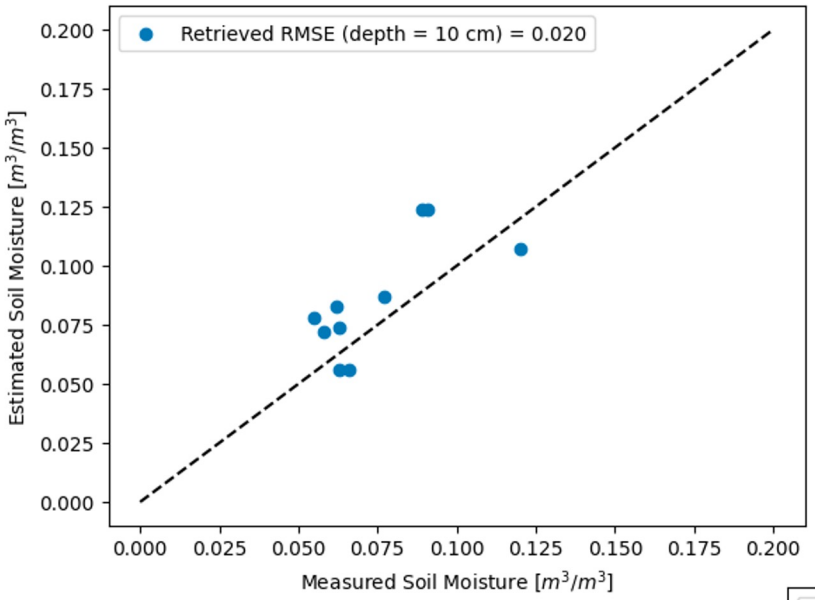
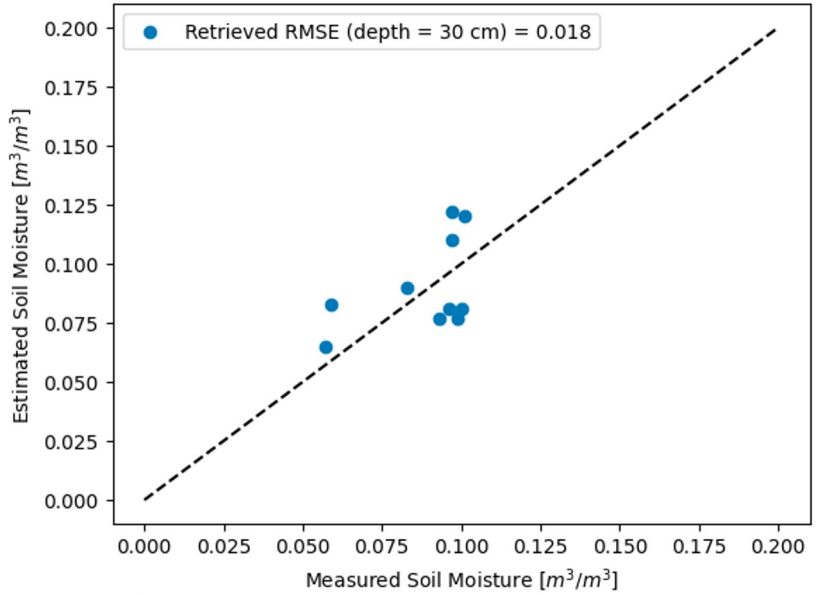
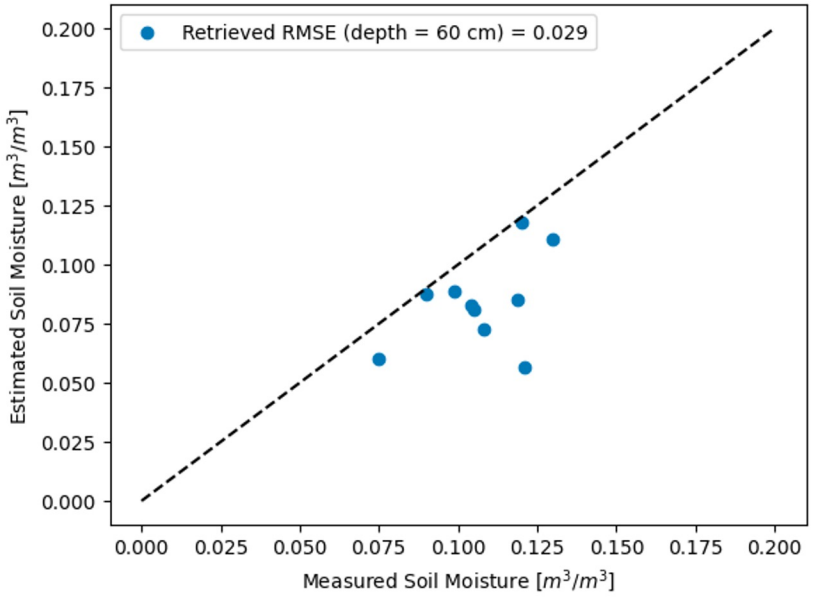
SlimSAR: P-Band preliminary results

Retrieval Errors for the Late Summer 2022 Campaign







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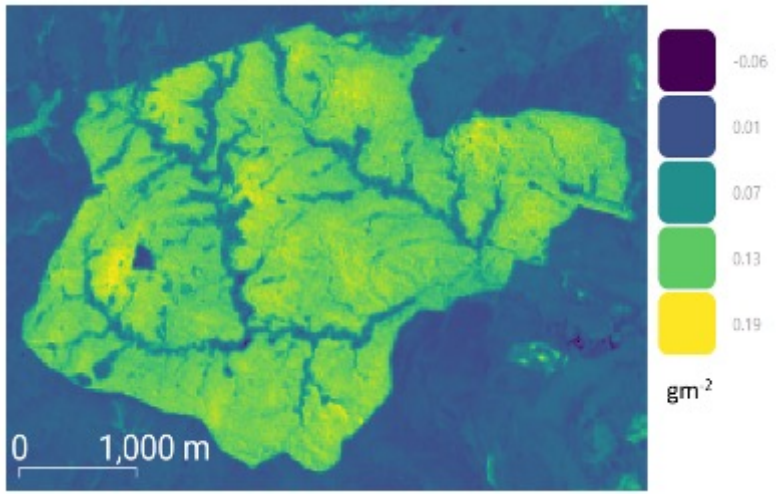
Forest Flows - The Pulse of the Forest - Digital Twin

Real Space

Data

Information

Virtual Space



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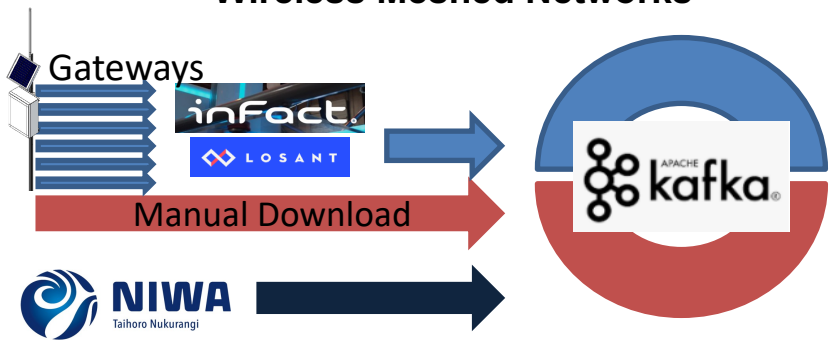
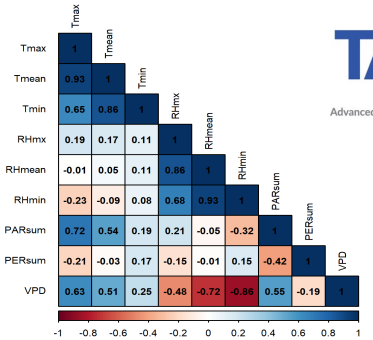


Analysis, Data Fusion, Machine Learning



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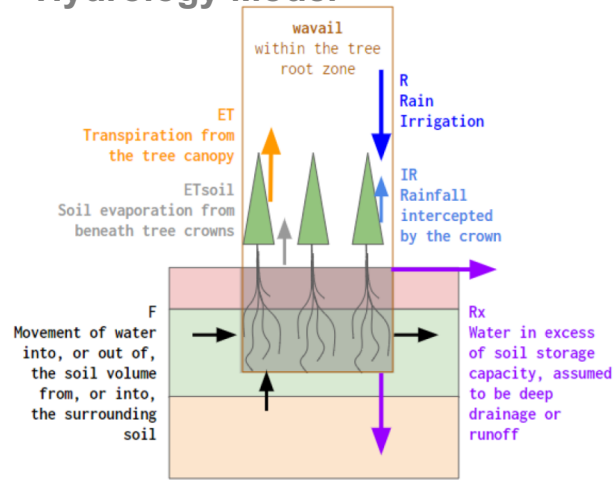
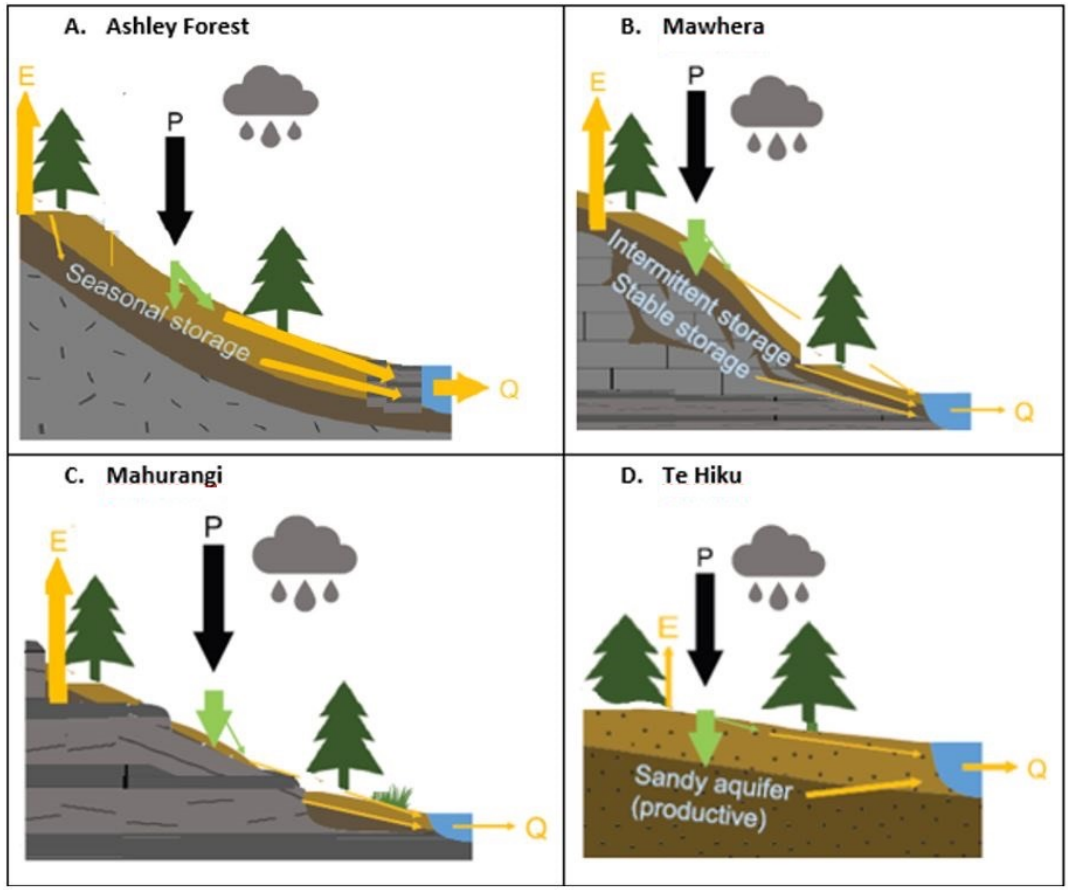
CABALA-W Catchment Hydrology Model



Summary

- Forest Flows programme uses an integrated system of above and below ground measurements to better understand planted forests hydrology
- Preliminary results from different measurements independently align
- Kafka Big Data Pipeline efficient approach with streaming, cleaning, storing, and accessing multiple datasets
- SlimSAR L- & P-Band airborne radar retrieval successful in forests with dense canopy & with steep topography
- SlimSAR focused on soil moisture retrieval, but backscatter collected for the above ground biomass
  - Looking for partners to process this data
- Multiple analyses approach
  - no one individual approach to rule them all
- Data fusion of terrestrial and remote sensing data starting this summer – new learnings??
- Programme ends mid-2024



Dean Meason
Senior Scientist
Dean.Meason@scionresearch.com

www.scionresearch.com
www.forestflows.nz

Date: 8/03/2023