Kiritimati Atoll, Kiribati –Photo T. Falkland

Characterising Hydrological Response in Changing Environments in Atoll Countries

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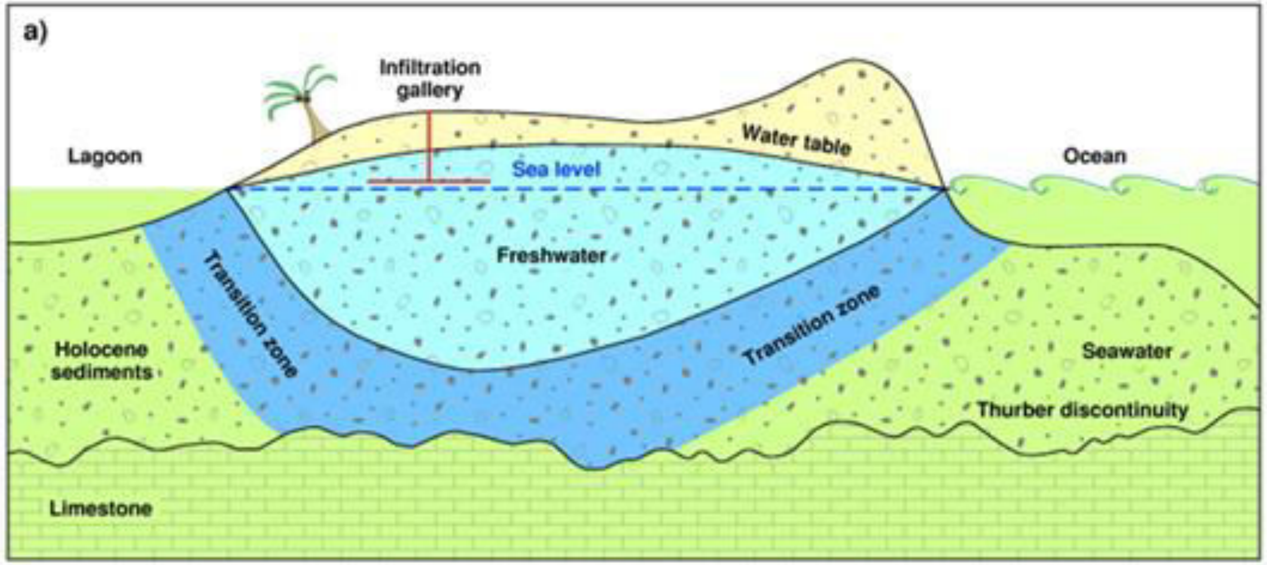
Why Atolls?

Male, Maldives, I. W photo

- Unique hydrogeology
- Highly dynamic & very variable climates
- Extreme hydrological responses
- Frequent natural disasters
- Rapidly growing populations & development
- Very vulnerable water resources
- Wider implications?

Unique Hydrogeology of Atolls

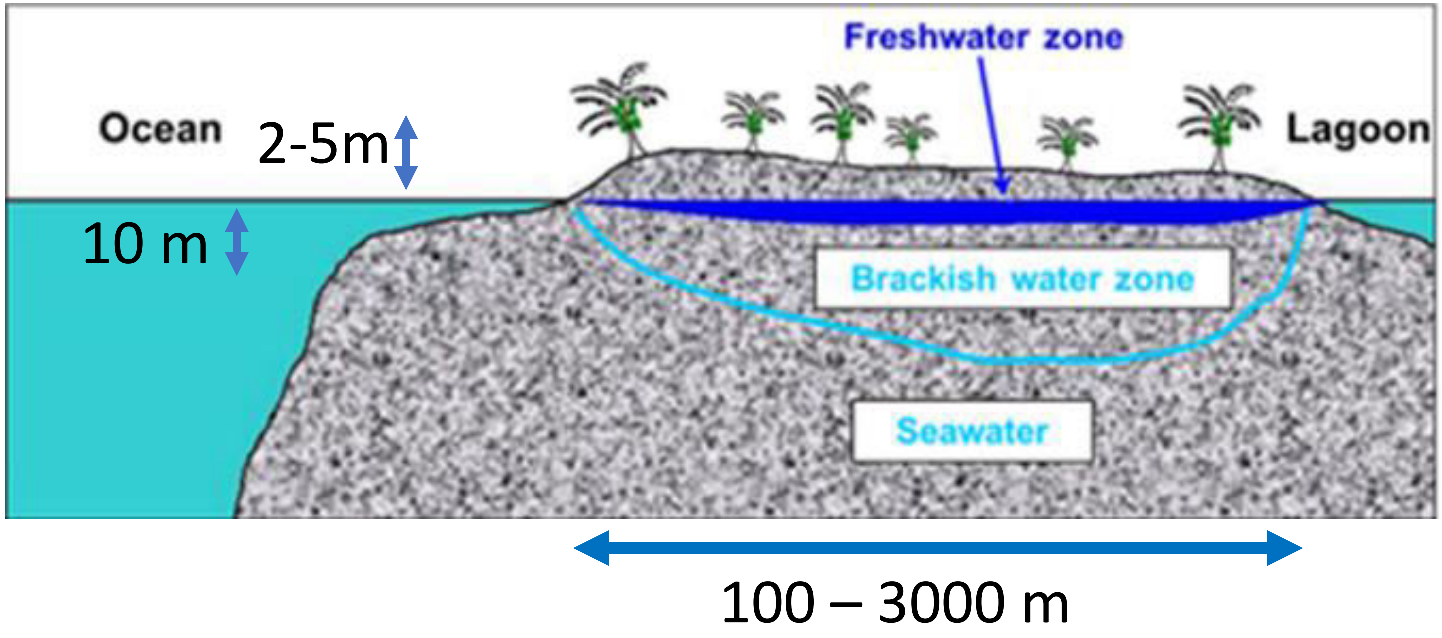


Dixon-Jain *et al.*, 22014

Distorted vertical scale

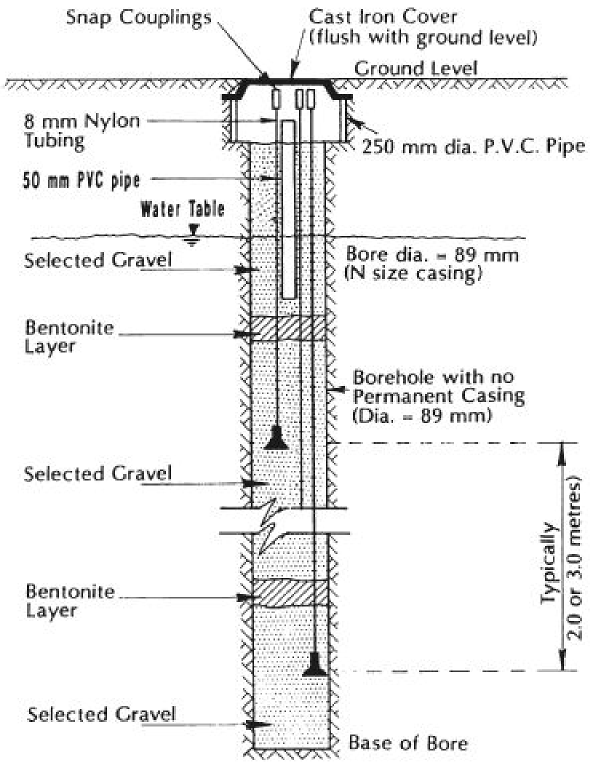
- Low elevation, 3-5m above msl
- Unconsolidated Holocene sediments, $K_0 \approx O(10\ \mathrm{m/day})$
- Deposited unconformably over karst Pleistocene limestone, $K_0 \approx O(1000\ \mathrm{m/day})$
- Shallow Ghyben-Herzberg fresh groundwater lens (FGWL)
- Saline transition zone underlain by seawater

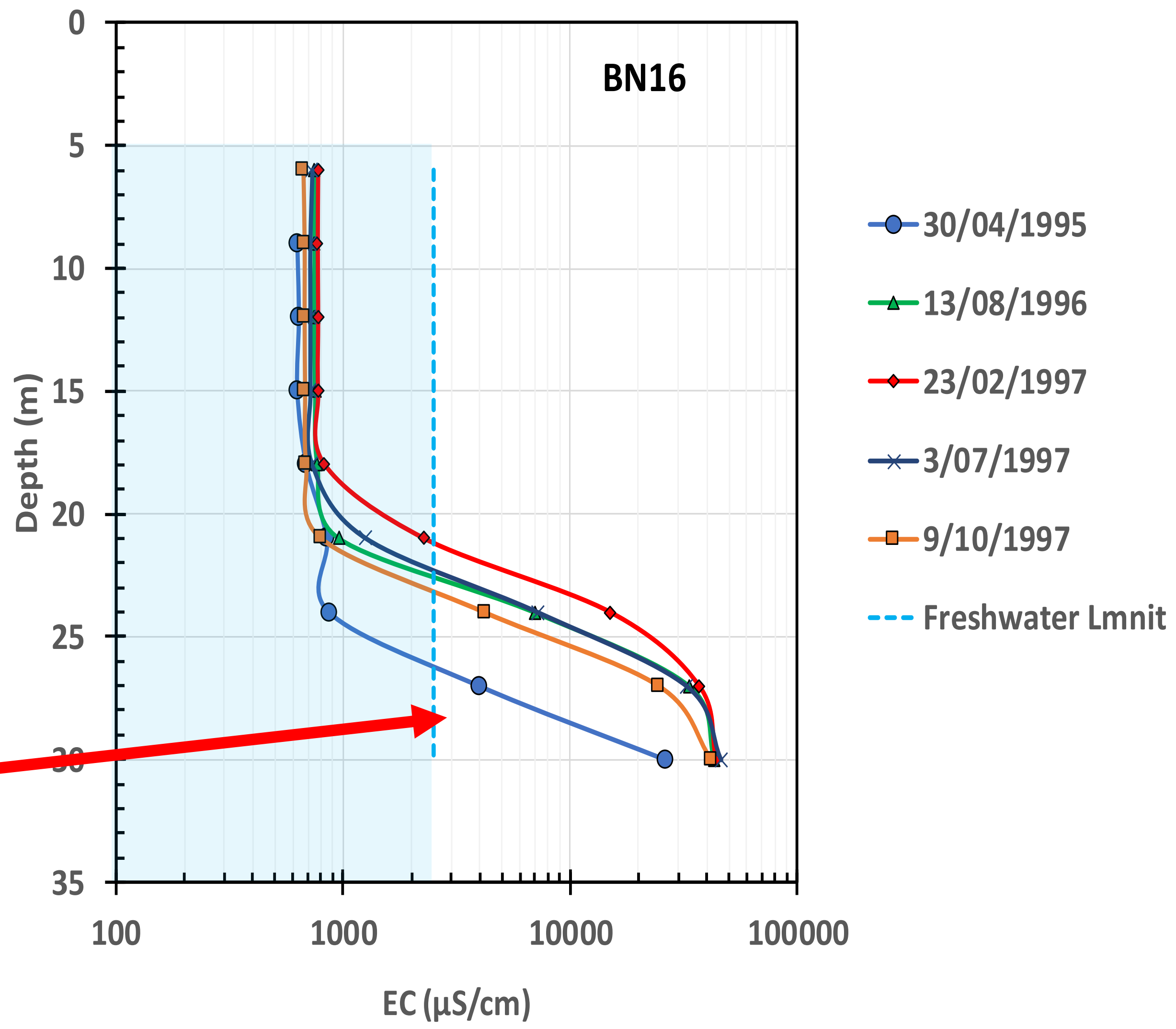
Unique Hydrogeology



- The shallow FGWL is a thin veneer of freshwater, maximum thickness =O(10m)
- Saline transition, max thickness =O(10m)

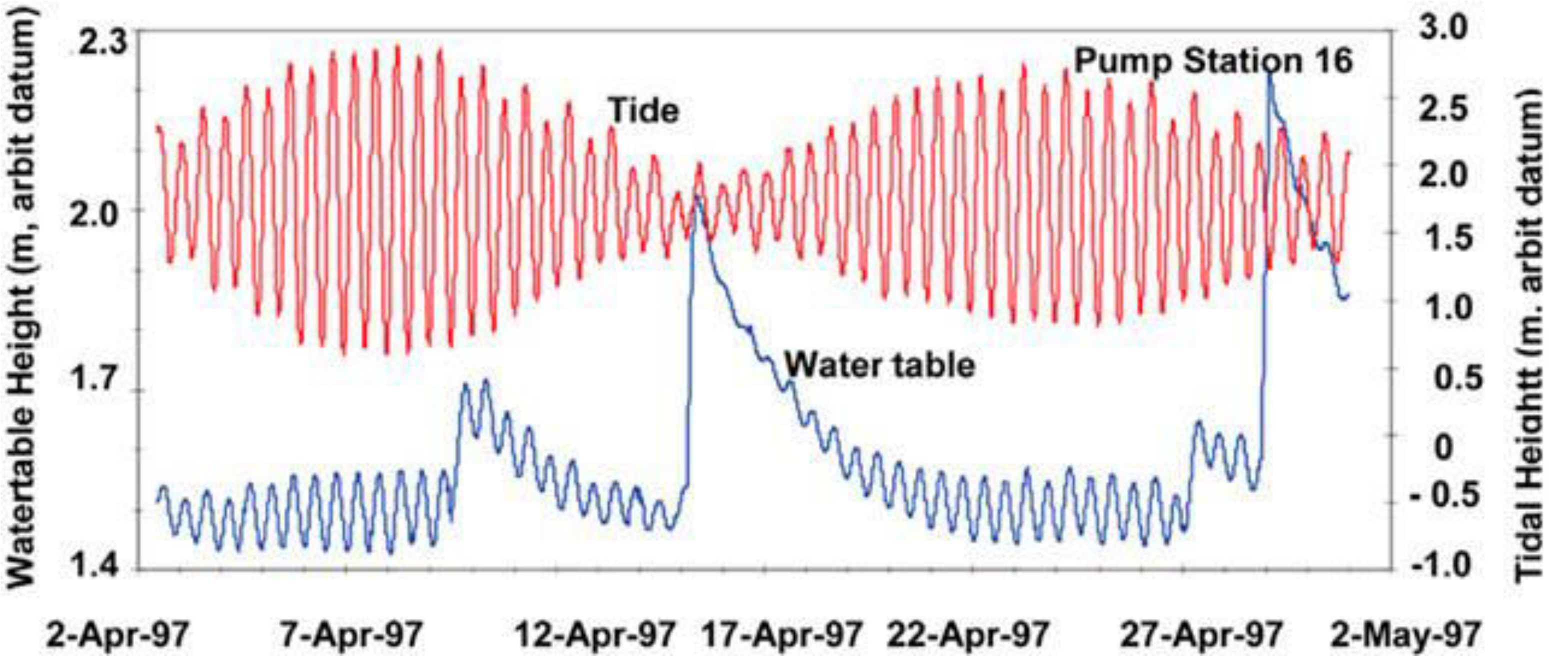
Depth & Salinity of Fresh Groundwater





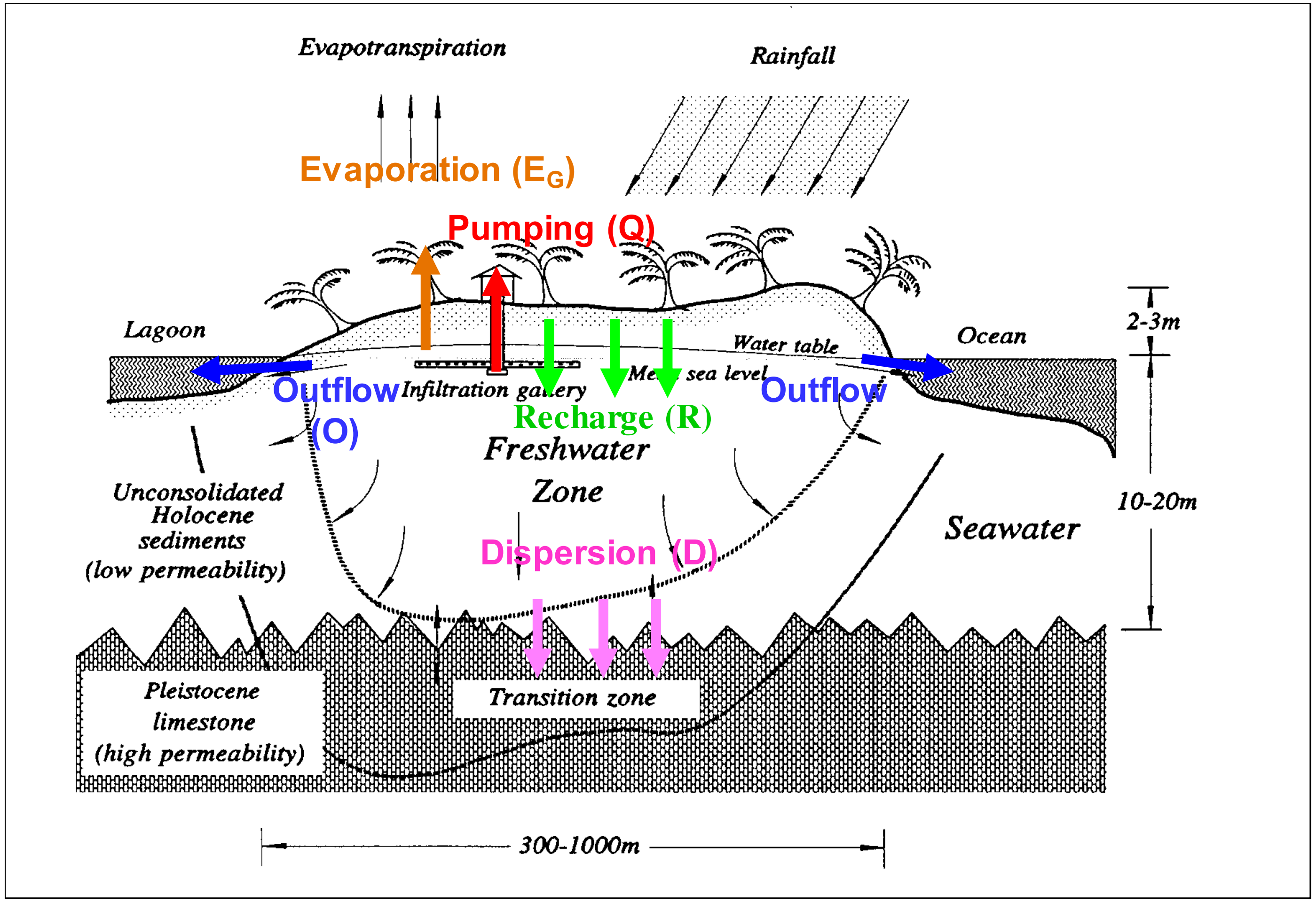
Freshwater limit EC = 2,500 µS/cm ≈ 1,500mg/L

Responses of the Water Table to Tides & Rainfall



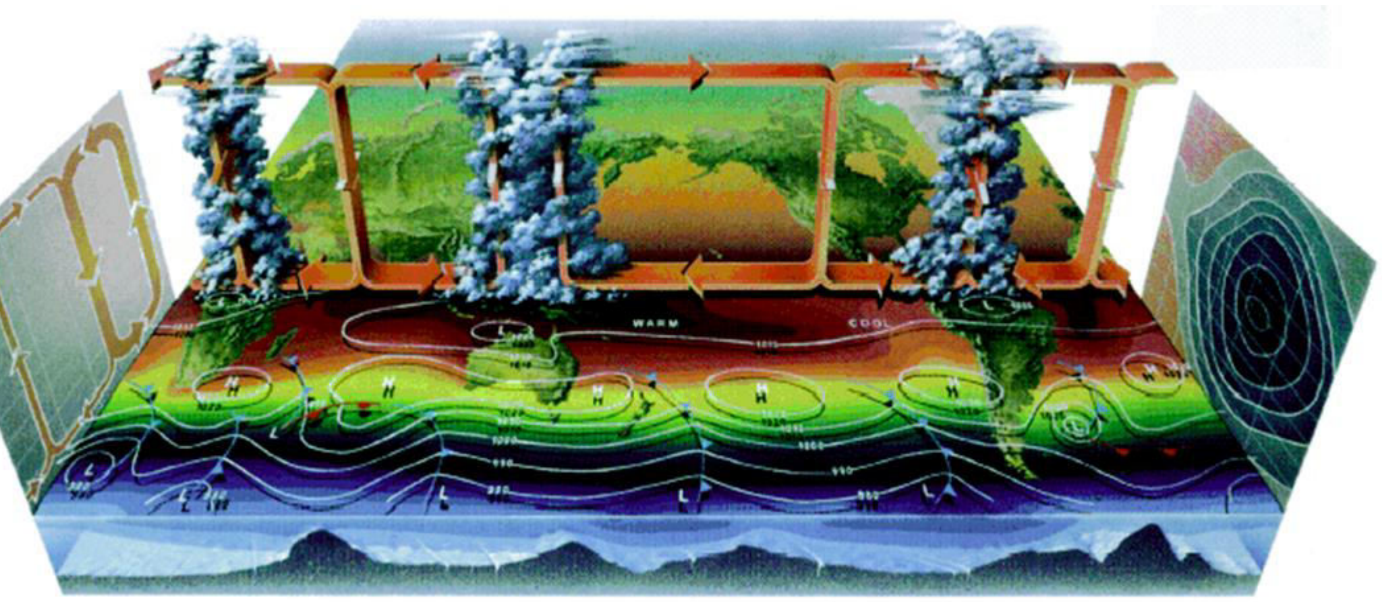
Water table fluctuates with oceanic tides and responds rapidly to rainfall recharge.
Decay due to discharge to ocean and lagoon and small ET losses.
The tidal fluctuations cause dispersive mixing between fresh groundwater and underlying seawater

Hydrological Processes



- Rainfall, *P*
- Evaporation, *ET*
- Groundwater Recharge, *R*
- Groundwater Outflow, *O*
- Dispersive mixing with underlying seawater, *D*
- Groundwater abstraction, *Q*
- The large K_0 of unconsolidated sediments mean that there is minimal natural runoff

Highly Variable Oceanic Rainfall

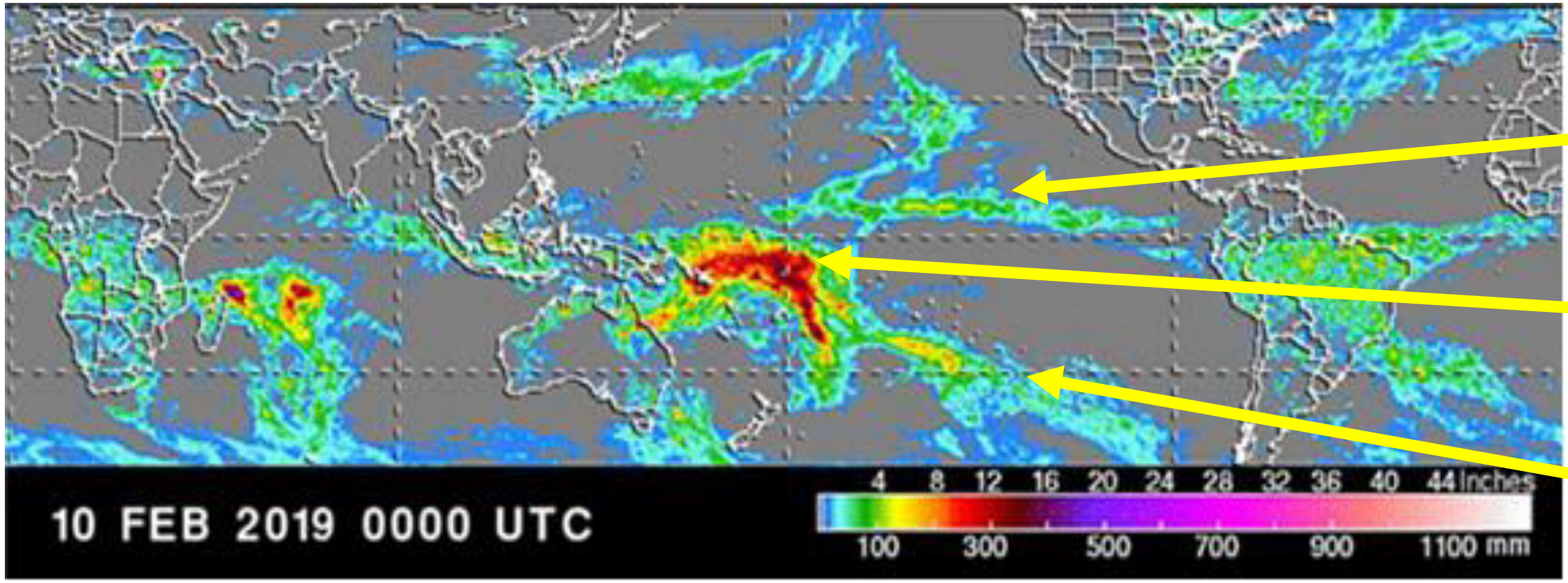


ABoM

Indian Ocean Pacific Ocean Atlantic Ocean

- Located in tropical/subtropical regions
- Massive, dynamic atmosphere/ocean heat & mass transfer over a vast area
- Spatially & temporally very variable

Spatially Variable 7-day Rainfall

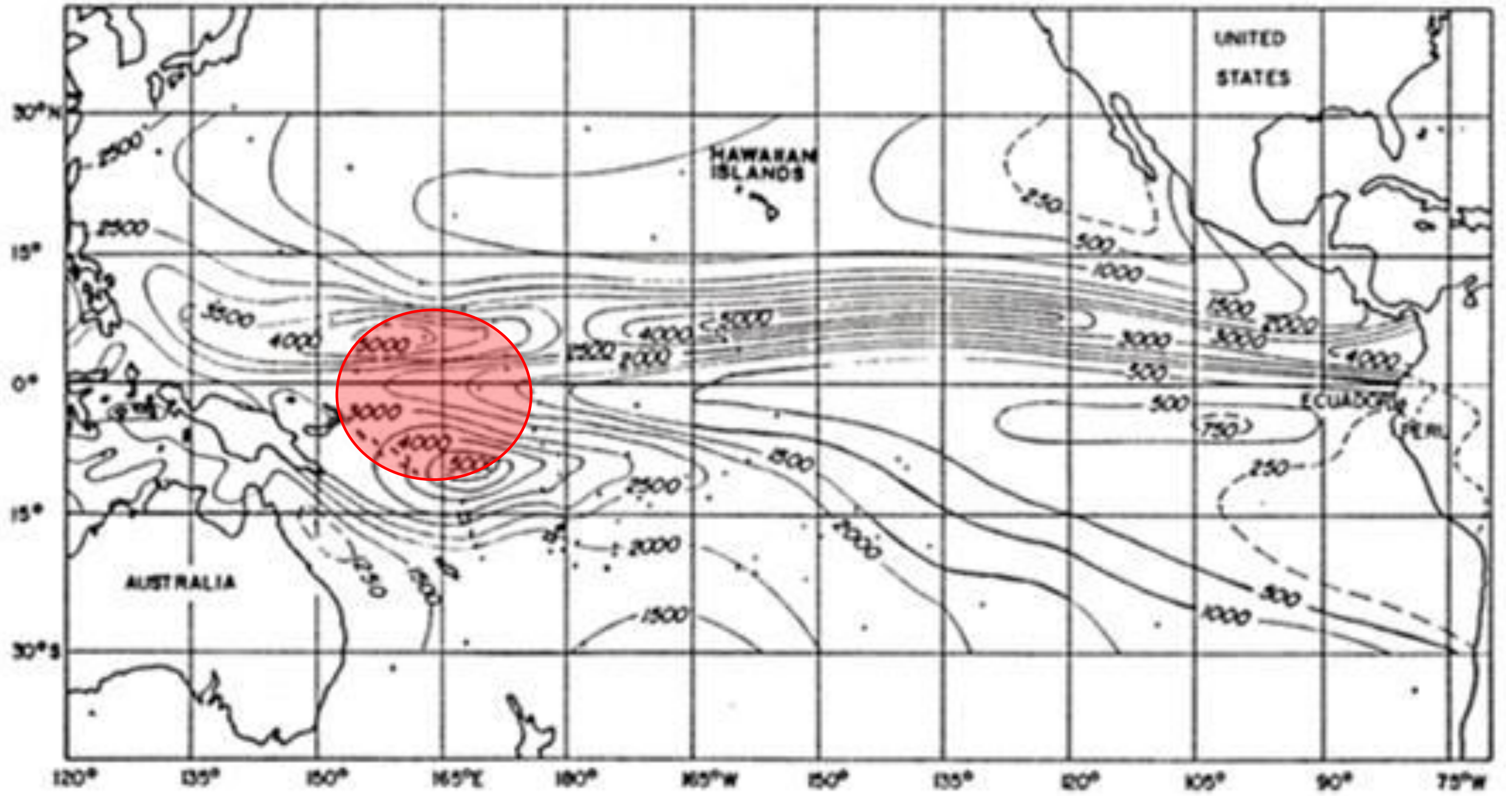


https://pmm.nasa.gov/TRMM/realtime-3hr-7day-rainfall

Areas of high rainfall

- Inter Tropical Convergence Zone, ITCZ
- Western Pacific Warm Pool, WPWP
- South Pacific Convergence Zone, SPCZ

Spatially Variable Mean Annual Rainfall



UNESCO 1993

ITCZ, SPCZ & WPWP dominant

250 < P_{12} < 5,000 mm at sea level

Also, large temporal variability in P_{12}

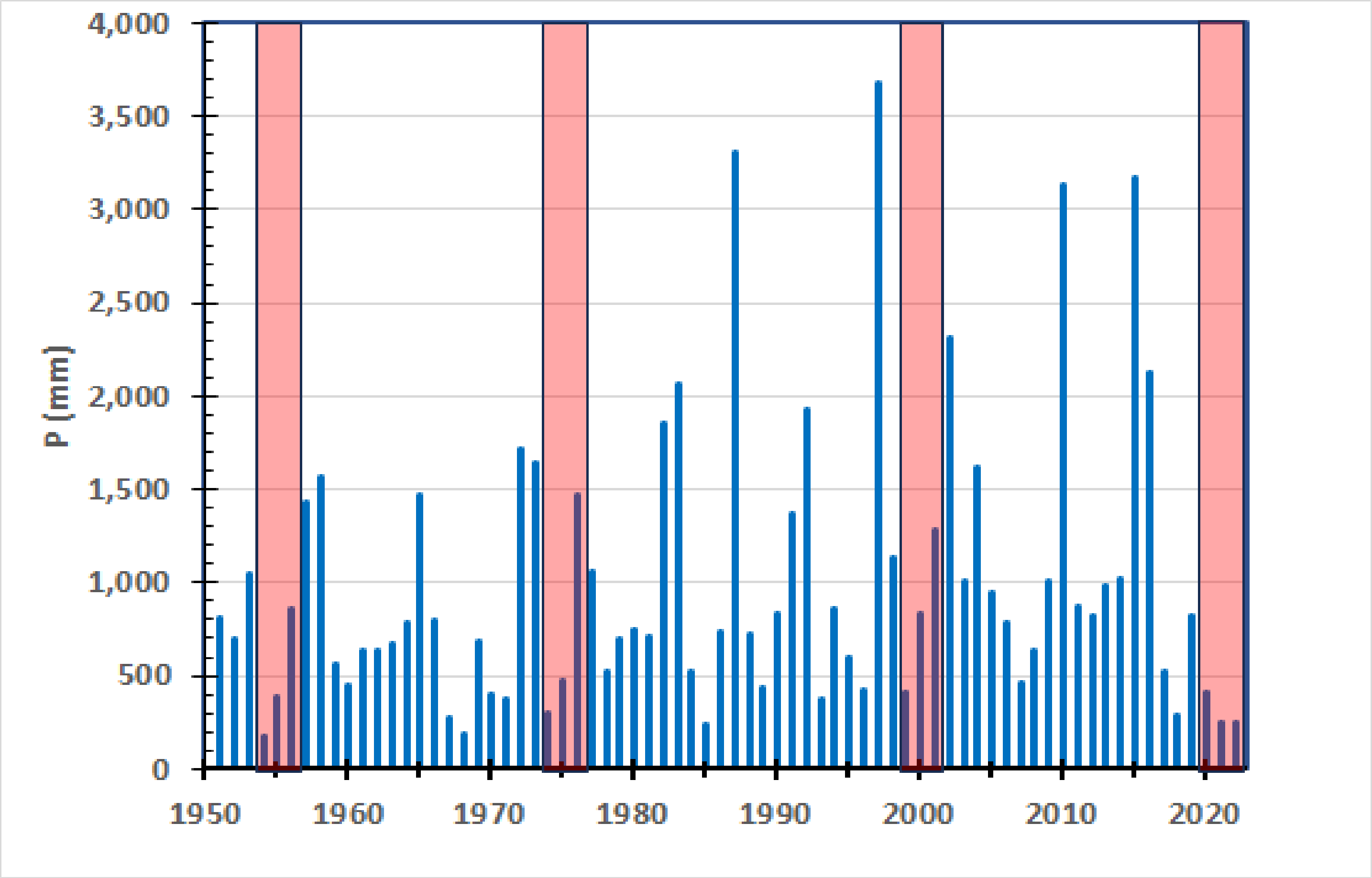
Movement of the WPWP along the equator ➔ENSO events, El Nino and La Nina, which change the position of the ITCZ and SPCZ rain bands ➔extreme variability of rainfall, particular in locations close to the equator

Temporally Variable Rainfall – La Nina Impacts

Google Earth

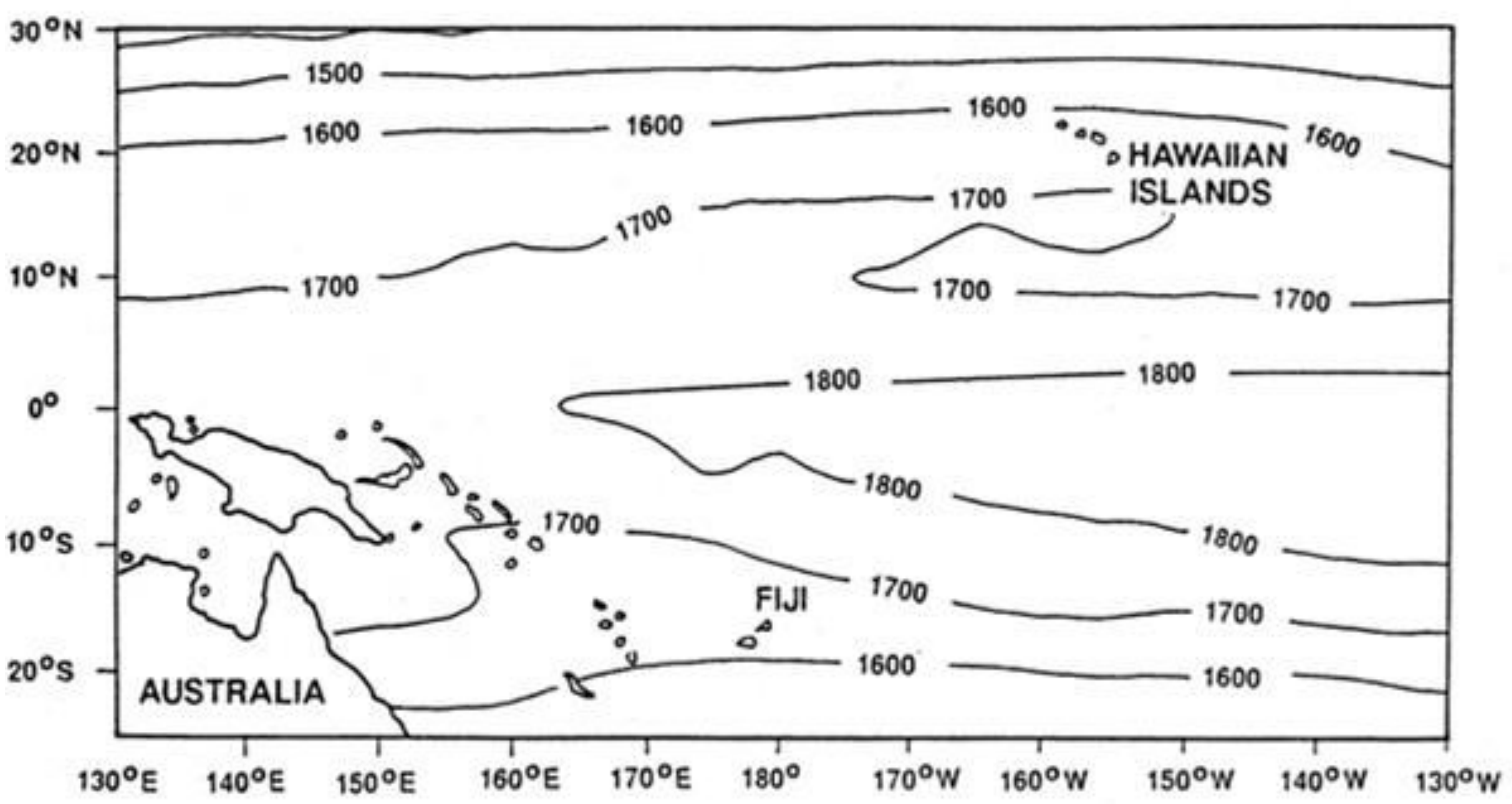
$177 \leq P_{12} \leq 3700$ mm

$IoV_{12} = 3.0$



Triple La Ninas since 1950

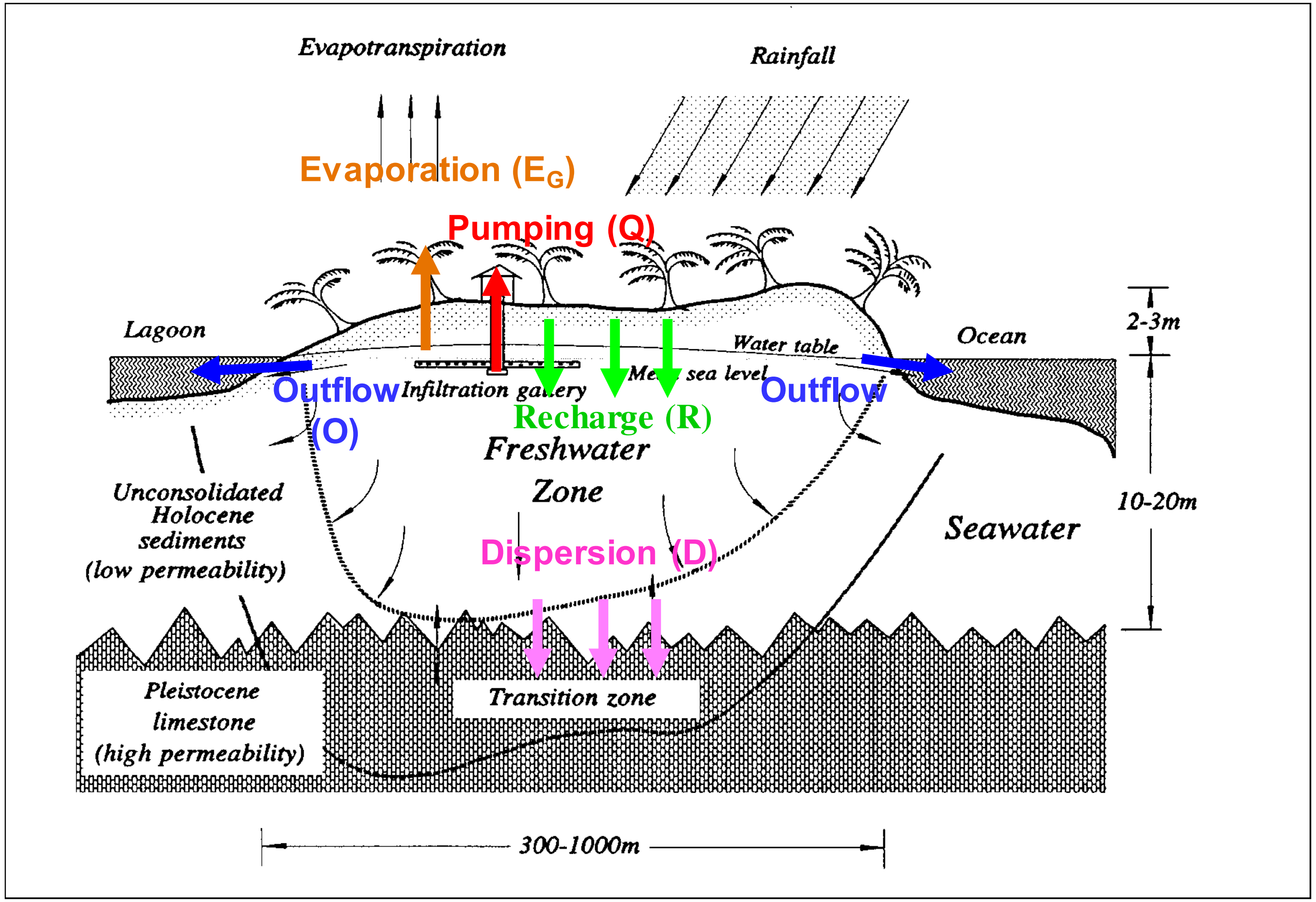
What about Evaporation?



Nullet (1987)

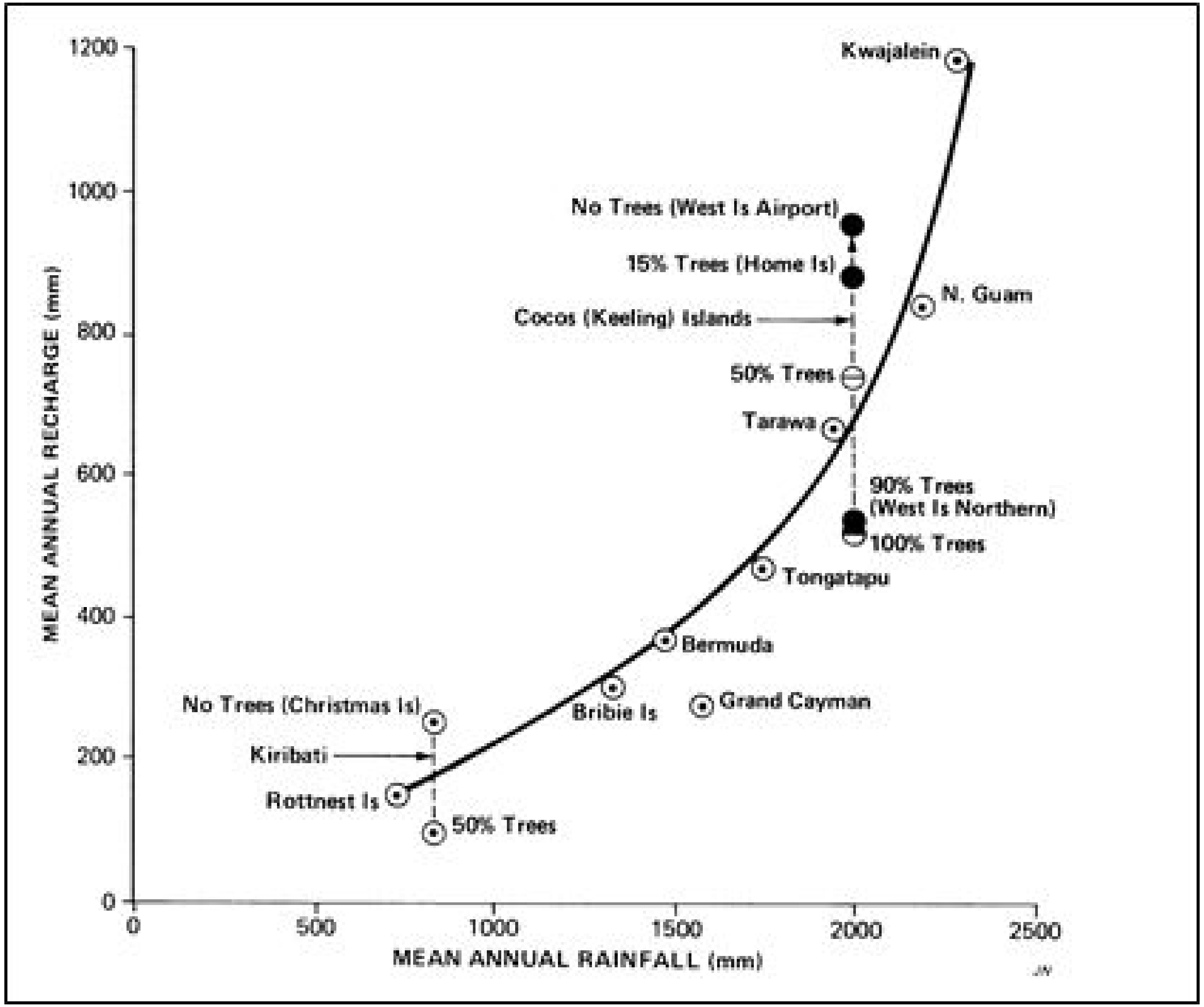
- Evaporation is much less well characterised than rainfall in islands
- Latitudinal radiation dependence perturbed by regional rainfall bands
- Very limited island *ET* data

Groundwater Recharge, *R*



- Under natural conditions, minimal surface runoff due to very large K_0
- R dependent on rainfall less evapotranspiration, $P - ET$
- *ET* poorly characterised

Mean Annual GW Recharge & Annual Rainfall



Modified from Falkland, 1991

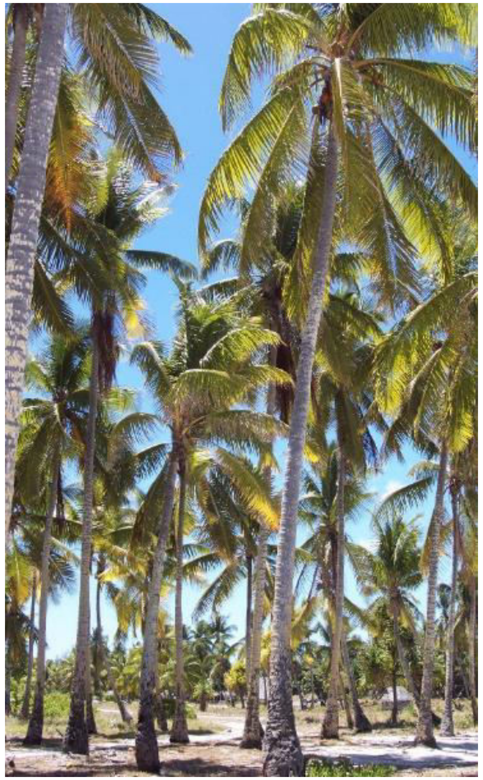
- Water balance estimates for different islands

  $0.2 < R/P < 0.5$

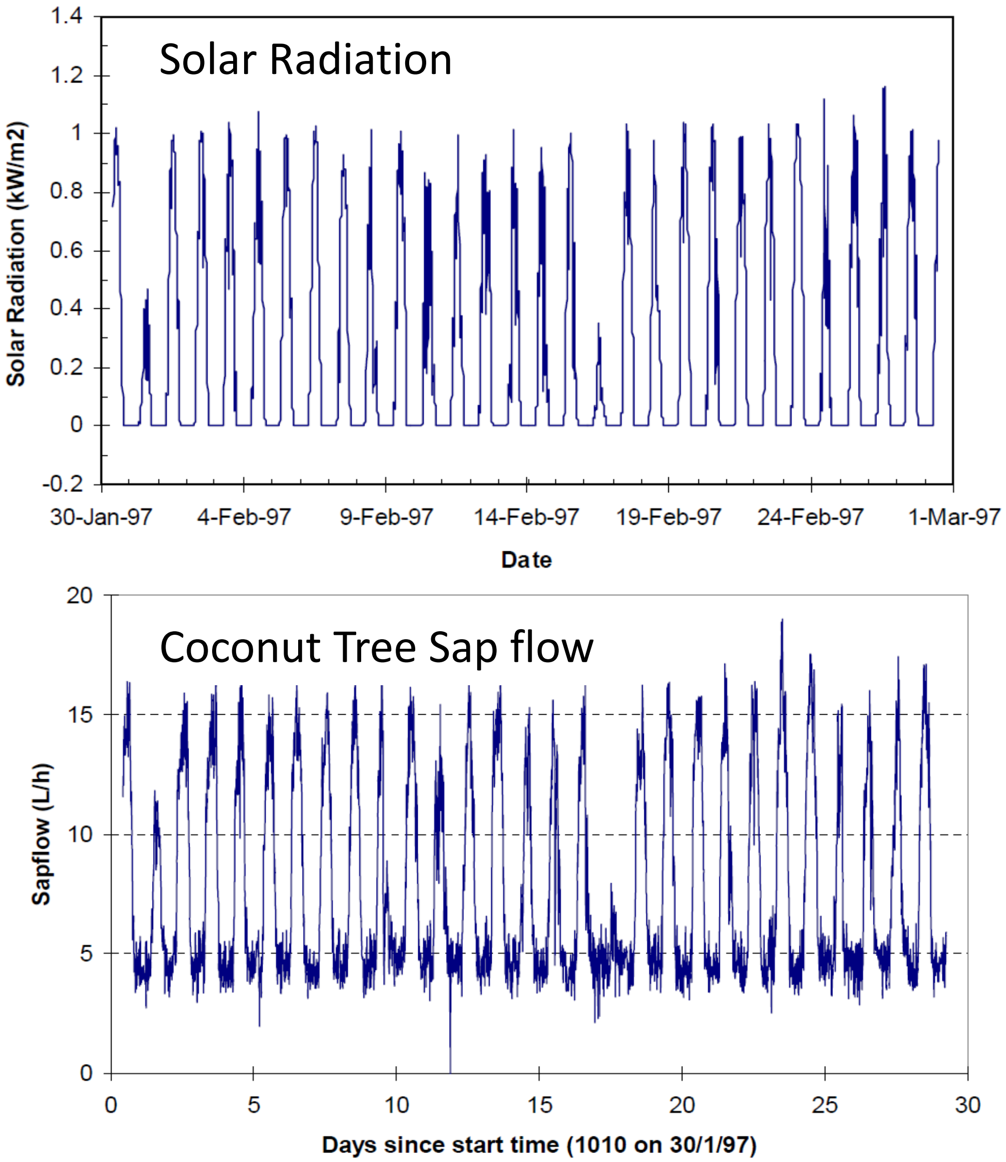
- Knowing mean recharge rates vital for identifying sustainable pumping rates

- Recharge dependent on fraction of tree cover because of *ET*

Direct Evapotranspiration Losses from GW by Trees



White *et al.*, (2002)



- Trees extract water from capillary fringe above shallow groundwater in response to solar radiation.
- Trees act like net radiometers
- On average transpire about 150 L/tree/day
- Need more measurements!

A Steady State View of Highly Dynamic Hydrology?

Fakaofo Atoll, Tokelau, photos Anesh Kumar SPC

- Groundwater is highly dynamic
- BUT mean residence time of GW is 10-40 years
- Droughts can last 3 years
- Steady state mean analysis can reveal critical properties and their functional dependence
- Volker *et al.* (1985)

Functional Dependence of Depth of FGWL

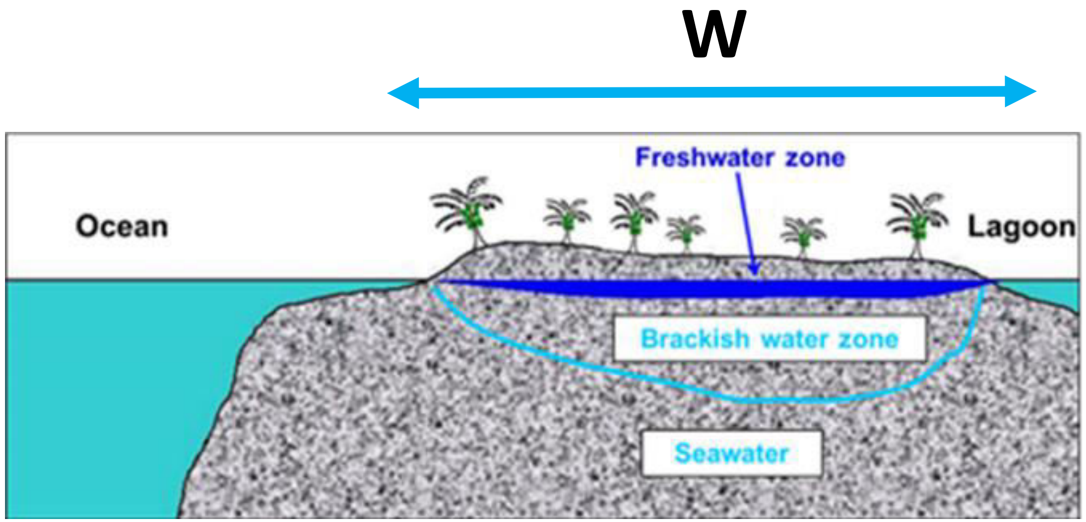
Steady state approximation

$$H_u = \frac{W}{2}\left[(1+\alpha)\frac{R}{2K_0}\right]^{1/2}$$

R (m/y) mean annual groundwater recharge rate

K_0 (m/y) horizontal saturated hydraulic conductivity

$$\alpha = (\rho_s - \rho_0)/\rho_0$$



Typically, H_u = O (10 m)

Critical factors: island width, R/K_0, and α

$$W < 250\text{m} \quad R/K_0 \downarrow \rightarrow H_u \approx 0\, m$$

Thickness of Saline Transition Zone (STZ), δ_u

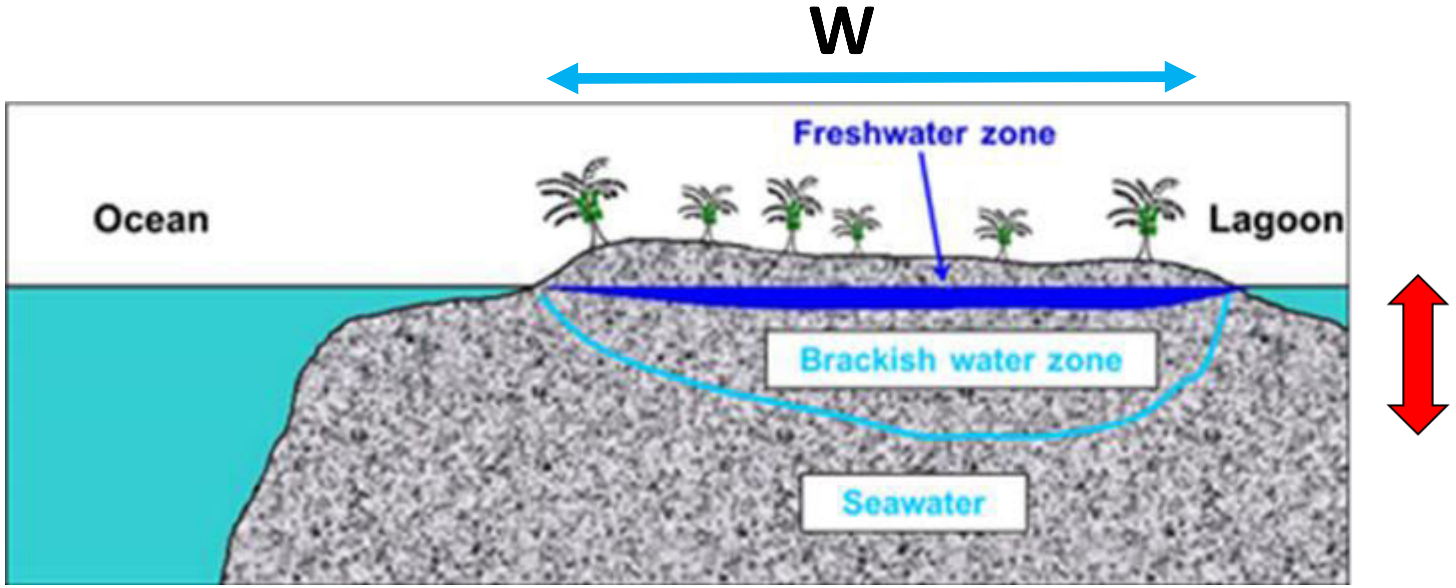
$$\frac{\delta_u}{H_u} = \frac{K_0}{R}\left(\frac{D}{\alpha W K_0}\right)^{1/2}$$

R (m/y) mean annual groundwater recharge rate

K_0 (m/y) saturated hydraulic conductivity

D (m^2/y) salt dispersion coefficient

$$\alpha = (\rho_s - \rho_0)/\rho_0$$



Typically, $7 \leq \delta_u \leq 15$ m

Critical parameters R/K_0, *atoll Peclet no,* $\alpha W K_0 / D$

Useable freshwater lenses exist in general when

$$\delta_u < 2H_u$$

Drought Impacts on Thickness of Freshwater, H_d, and STZ, δ_d

$$H_d / H_u = (R_d / R)^{1/2}$$

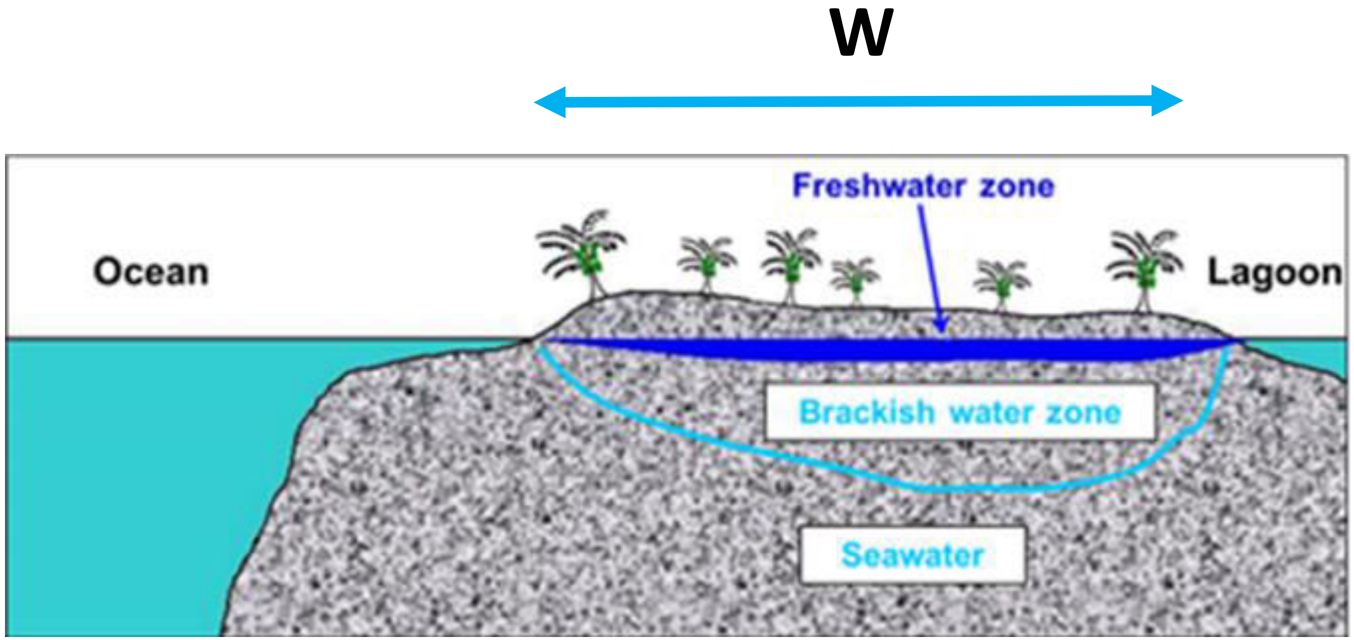
$$\delta_d / \delta_u = (R / R_d)^{1/2}$$

R (m/y) mean annual groundwater recharge rate

R_d (m/y) recharge rate during drought

u: unpumped mean value

d: value during drought

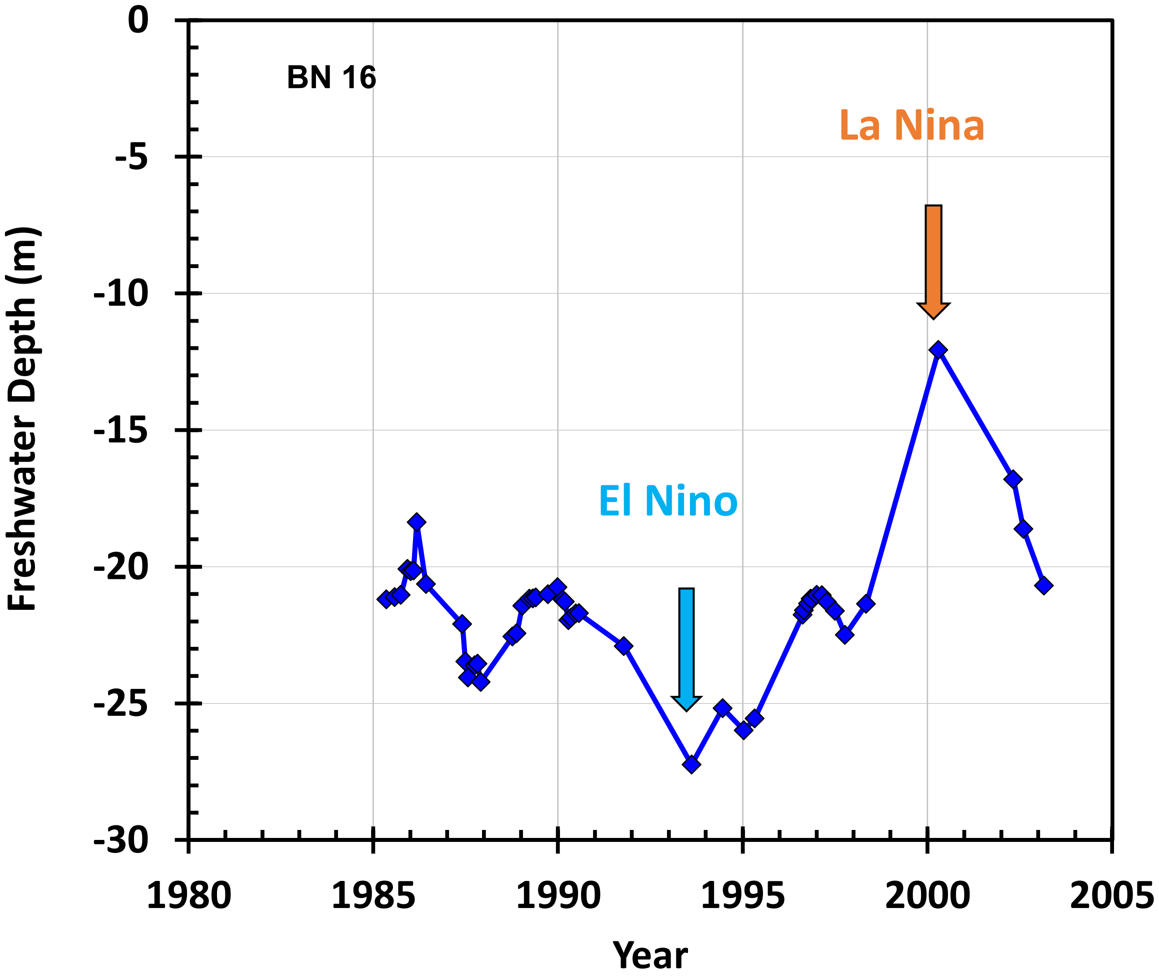


Typically, $H_d = ½ H_u$

$\delta_d = 2\,\delta_u$

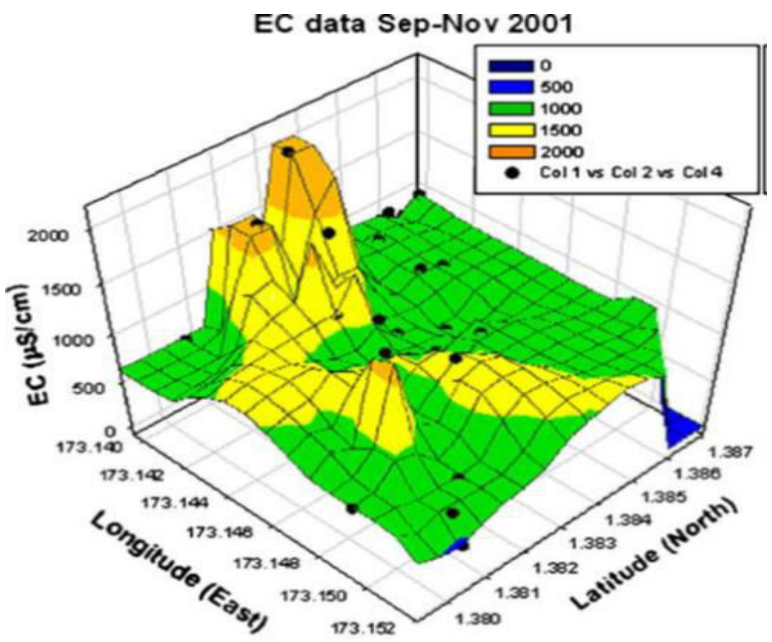
Critical parameter $(R/R_d)^{1/2}$

Impact of ENSO Events on Freshwater Lens Thickness

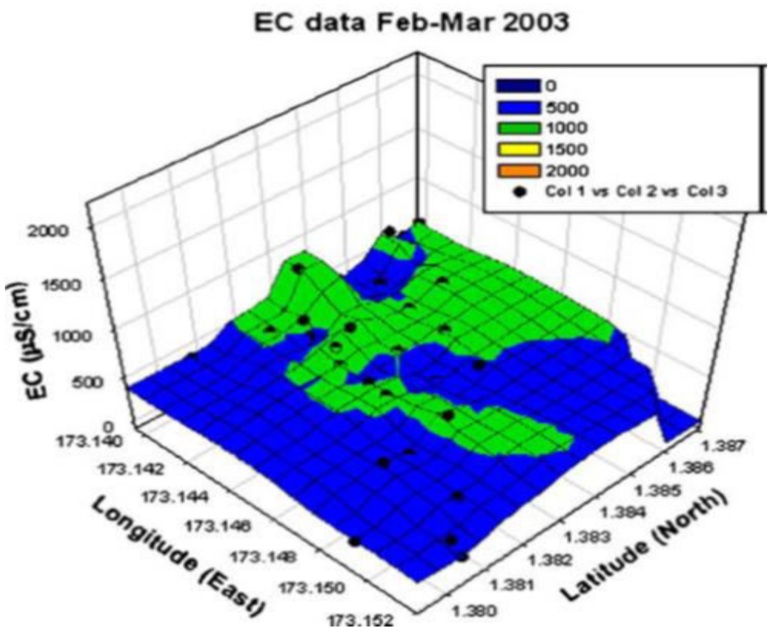


H_d at end of a triple La Nina 44% of H_u during a moderate El Nino event

Impact of ENSO Events on Groundwater Salinity



End of Triple La Nina event

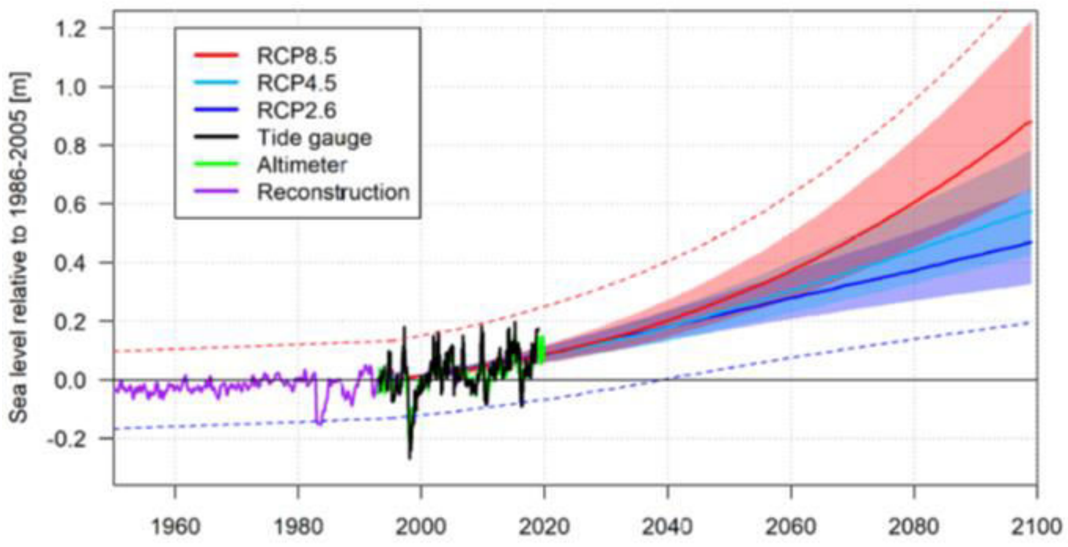


End of moderate El Nino event

Groundwater salinity reveals heterogeneity of the unconsolidated aquifer

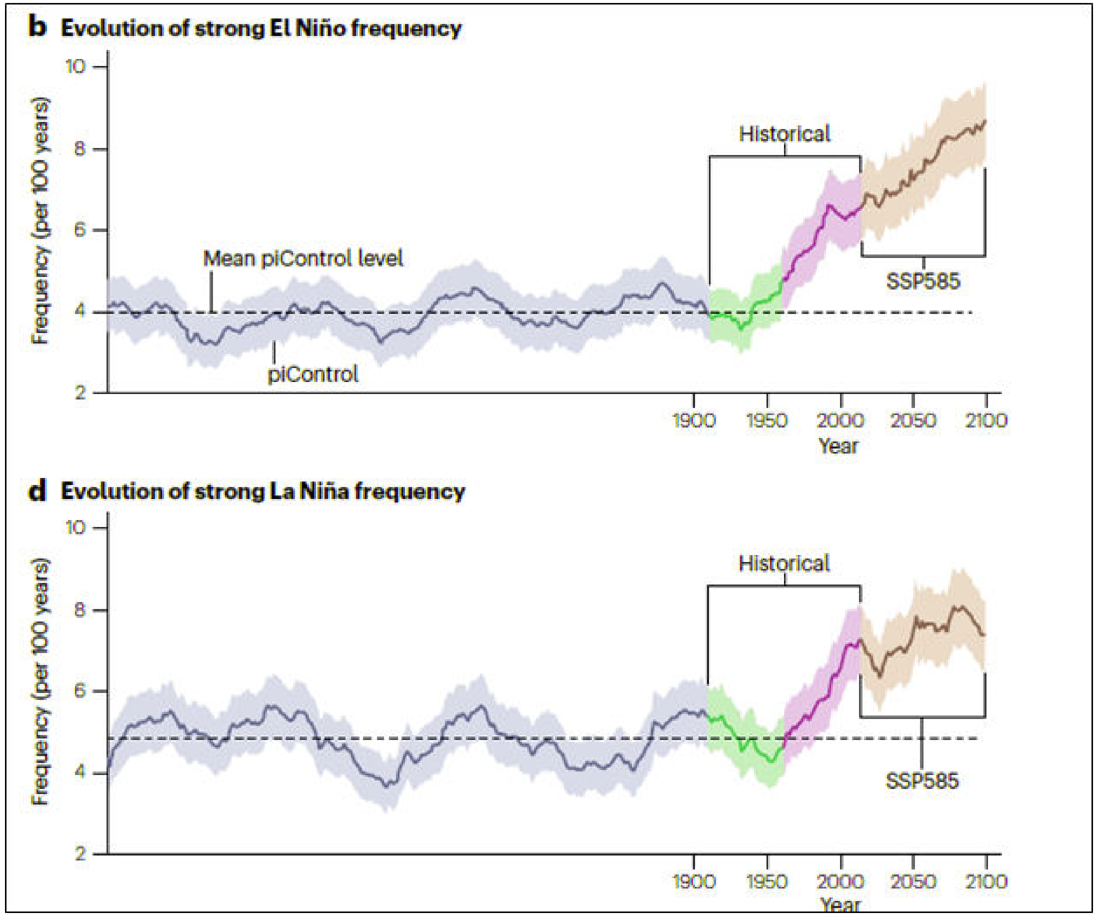
Major Future Natural Challenges for Atoll Groundwater

CSIRO & SPREP (2021) https://doi.org/10.25919/f4jf-nx47

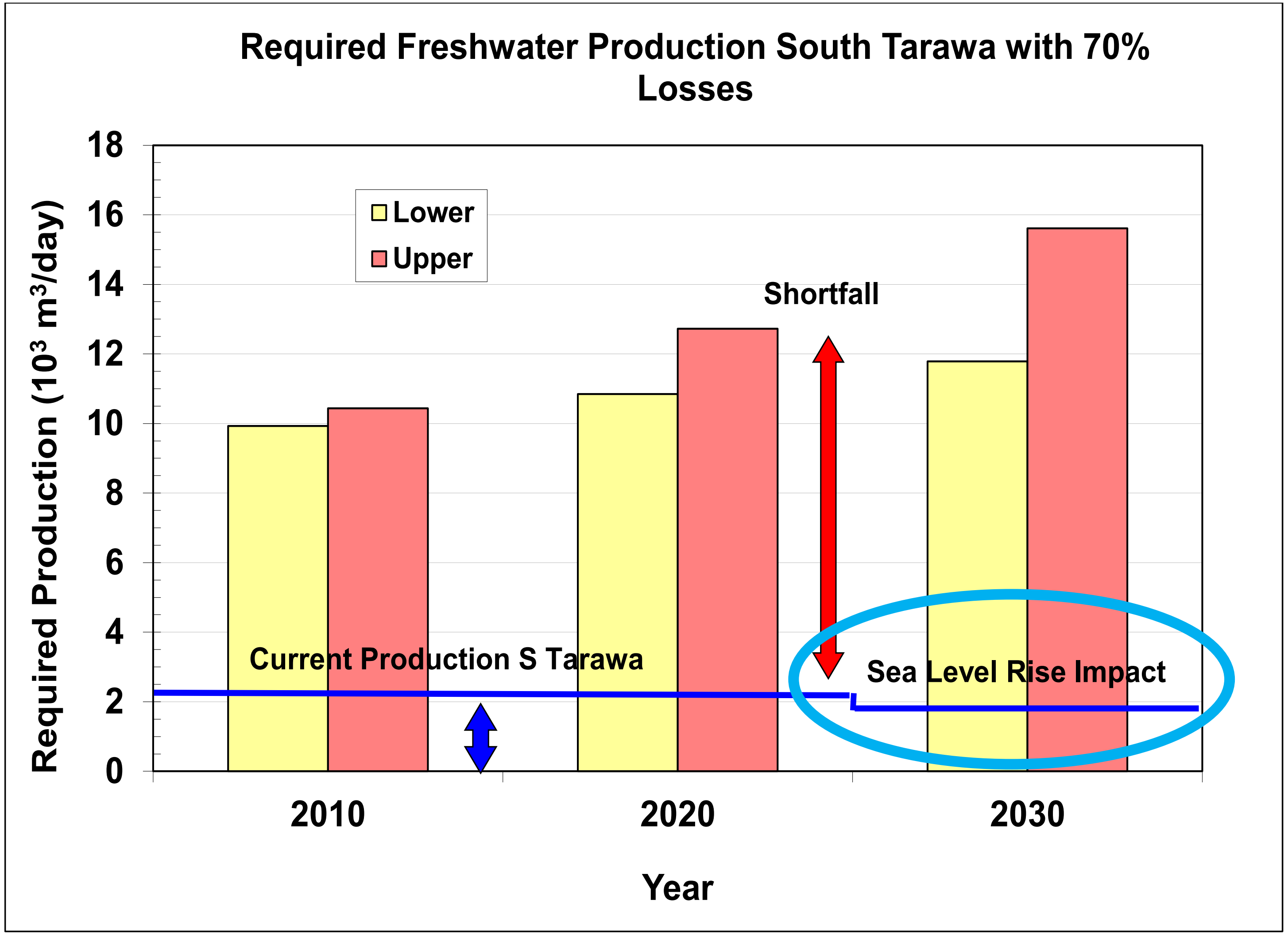


- Future sea level rises & island inundation
- Change in frequency of severe ENSO events

Cai et al (2023) https://doi.org/10.1038/s43017-023-00427-8



Future Population & Development Challenges



White (2010)

In some islands demand for freshwater already exceeds the sustainable groundwater yield.

Summary

North Tarawa Kiribati photo IW

- Changes in climate, extreme events, sea level, development & water demands in atoll countries require improved understanding of hydrological responses.
- Simple steady state analysis identifies the critical properties & functional dependence
- There is limited hydrological data in atolls
- Future challenges require better understanding of ET & ENSO
- Do atolls provide lessons for all of us?

Thank you

State Key Laboratory of Water Resources Engineering & Management, Wuhan University

Mogmog Island, Ulithi Atoll, Yap, FSM – photo IW