Newborough Warren

What's Happening to the Water Under the Dunes?

A 21-year groundwater study at one of Wales's most important coastal dune sites

Hollingham, M. (2026). Hydrogeological Dynamics, Behavioural Clustering and Management Intervention Analysis at Newborough Warren Coastal Sand Dune Aquifer, Wales. Draft, March 2026.

Project: github.com/newbroman/Newborough_Hydrology

Web tools (scenario viewer, flood forecaster): newbroman.github.io/Newborough_Hydrology

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The place

Newborough Warren sits at the southern tip of Anglesey, covering roughly 1,300 hectares of sand dunes, wetlands and conifer plantation. It is designated as a Special Area of Conservation — one of the most important coastal dune systems in Wales.

The site is home to rare plant communities called *dune slacks*: low-lying hollows between the dunes where groundwater rises close to the surface each winter, creating seasonally flooded wetlands that support creeping willow, orchids and a rich variety of wetland invertebrates.

The survival of these habitats depends entirely on groundwater. If the water table sits too low in summer, the plant communities that define dune slacks shift irreversibly towards drier grassland. The difference between a thriving wet slack and a degraded dry one is remarkably small — just **37 centimetres** of water table depth in summer.

A large portion of the northern dunes was planted with Corsican pine between 1948 and 1965. This plantation intercepts roughly a quarter of incoming rainfall before it can reach the ground, reducing the amount of water that recharges the aquifer beneath.

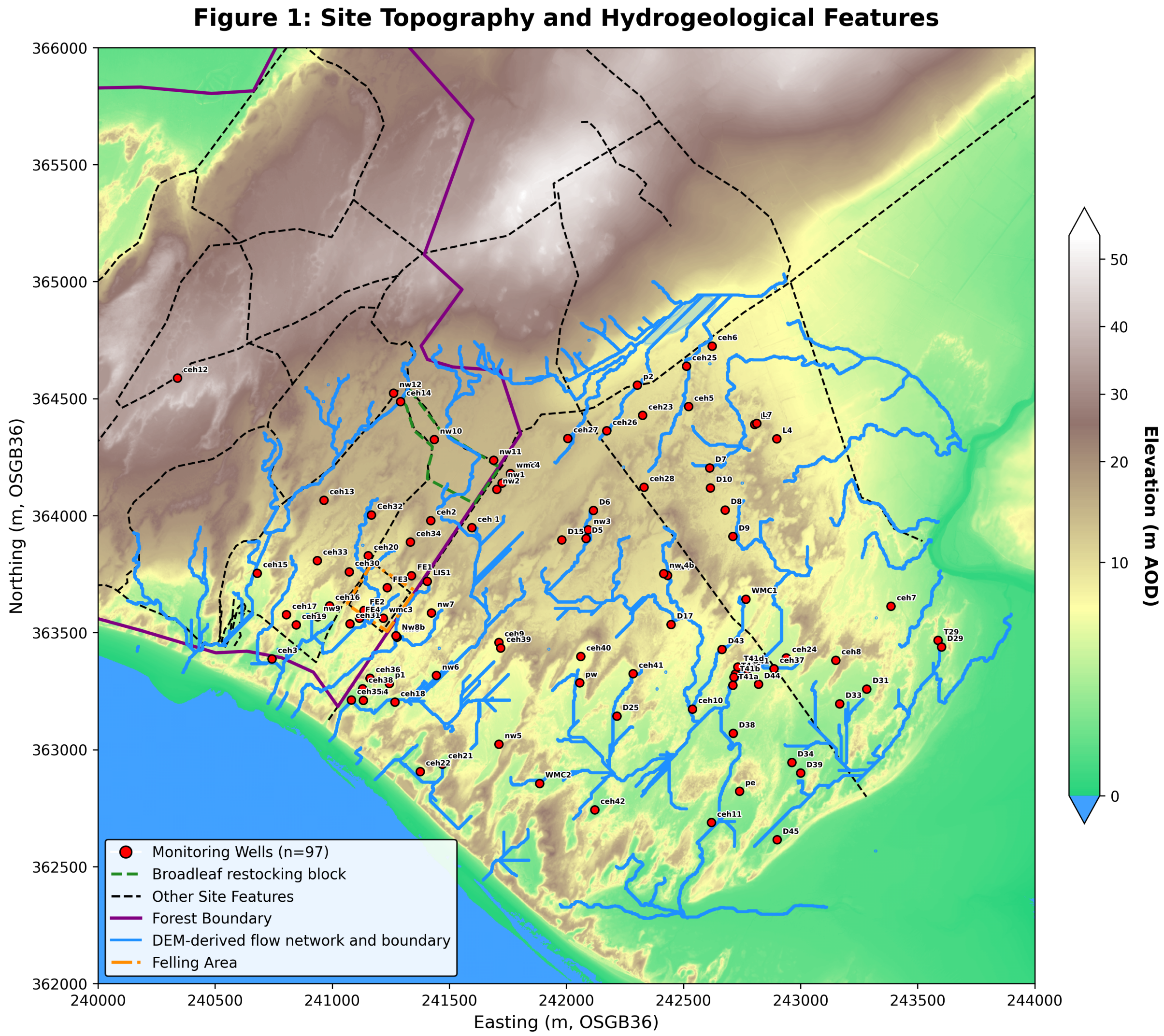

Figure 1. Site overview showing the topography of Newborough Warren, the 97-well monitoring network, the forest boundary (magenta), the 2017 felling area (orange), and the drainage network derived from the digital elevation model.

The study

I monitored 89 wells across the site for 21 years (2005–2026), measuring water levels monthly with simple hand-held instruments called dipwells. Combined with publicly available rainfall and temperature data from a nearby weather station, this network was analysed using a 26-step data pipeline to understand how the groundwater system works, how it is changing, and what management can realistically achieve.

The approach was deliberately designed to be low-cost and reproducible — no specialist equipment, no telemetry, no laboratory analysis — so that it could be replicated at other coastal dune sites facing similar challenges.

How the model works

At the heart of the analysis is a simple water balance equation fitted independently at each well. Each month, the change in water level is explained by three competing forces: **rainfall** pushing the water table up, **evaporation** pulling it down, and **drainage** carrying water sideways towards the coast or lake. The model estimates the strength of each force for every well, producing three coefficients that together define how that part of the aquifer behaves. Wells with similar coefficients are grouped into zones.

This state-space model (SSM) was benchmarked against a simpler transfer function approach that lacks the drainage feedback term. Figure 2 shows both models against observed water levels at CEH6, a Dune cluster well. In one-step diagnostic mode (top panel) the two models are comparable, but in iterative forecasting mode (bottom panel) — where the model runs forward using only climate data and its own previous predictions — the SSM maintains realistic seasonal cycles (NSE = 0.66) while the transfer function diverges (NSE = –1.1). The drainage term is what prevents the model from drifting.

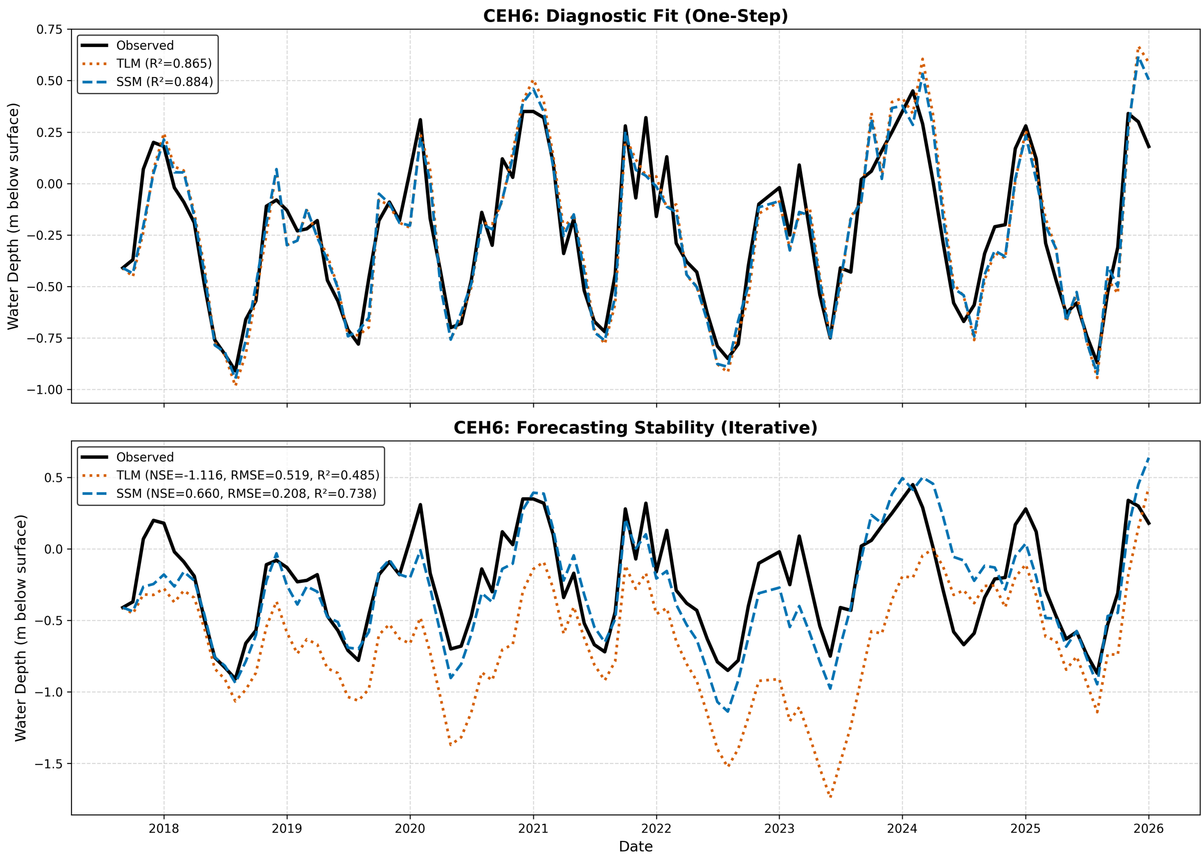

Figure 2. Model benchmarking at CEH6 (Dune cluster). Top: one-step diagnostic fit, where both the SSM (blue dashed) and transfer function (orange dotted) track the observed water level (black). Bottom: iterative forecasting, where the model runs forward using only climate forcing. The SSM maintains realistic amplitude and timing; the simpler model diverges progressively.

Seasonal prediction equations

Alongside the monthly SSM, a pair of seasonal prediction equations was fitted for each groundwater zone. A **winter equation** predicts the peak winter water level from cumulative winter rainfall (October–March) and the preceding summer minimum. A **summer equation** predicts the summer minimum from cumulative summer rainfall (April–September) and the preceding winter peak. Together these capture the aquifer's memory: how deep the summer drought was determines how much winter rain is needed to refill, and how high the winter peak reached determines how far the water table can fall the following summer.

For example, the Eastern Block summer equation is:

$$\textbf{Summer minimum} = 0.0016 \times P_{summer} + 0.51 \times h_{winter\ peak} - 1.57 \quad (R^2 = 0.63)$$

This says: for every additional 100 mm of summer rain, the summer minimum is 0.16 m shallower; and for every 0.10 m higher the preceding winter peak, the summer minimum is 0.05 m shallower. The intercept (–1.57 m) represents the structural deficit — even with average rainfall and an average winter peak, the summer minimum sits well below ground surface.

Critical rainfall thresholds

Because the SSM is a physical mass balance rather than a statistical correlation, it can be run forwards: given a measured summer water level and a forecast of winter rainfall, the model calculates whether the water table will rise high enough to flood a given slack. This produces a **critical rainfall threshold** for each well — the amount of winter rain needed to achieve flooding, expressed as a multiple (λ) of the long-term average. Wells where λ exceeds 2.0 — requiring twice the average winter rainfall — are classified as structurally unreachable under any winter in the 95-year record.

These equations are built into an interactive web tool (the *scenario viewer*) that allows site managers to explore how different management actions — tree felling, thinning, broadleaf conversion, dune scraping — and future climate scenarios would shift water levels across the entire site. A companion *flood forecaster* converts a single dipwell reading into a probability of winter flooding, updated as the season progresses.

Five distinct groundwater zones

The analysis identified five distinct zones across the site, each behaving differently depending on its geology, position and land cover:

- **C1 — Lake Edge (eastern block):** Shallow water table, responds quickly to rainfall, drains fast. The closest to the ecological tipping point.
- **C2 — Dune (eastern block):** Classic open dune, moderate rainfall response.
- **C3 — Western Residual:** Acts as a deep buffer — slower to respond, holds water longer.
- **C4 — Main Forest:** Pine plantation on thin soil over bedrock. Trees intercept rain and the shallow substrate amplifies summer drying.
- **C5 — Coastal Forest:** Pine plantation on deeper coastal sand. Shows the steepest water table decline of any zone — declining nearly four times faster than the next worst.

A key finding is that it is the thickness of sand beneath each area — not the trees above — that controls how severely evaporation draws down the water table in summer. Within the forest zone, ground elevation alone explains 95% of the variation in this drying effect.

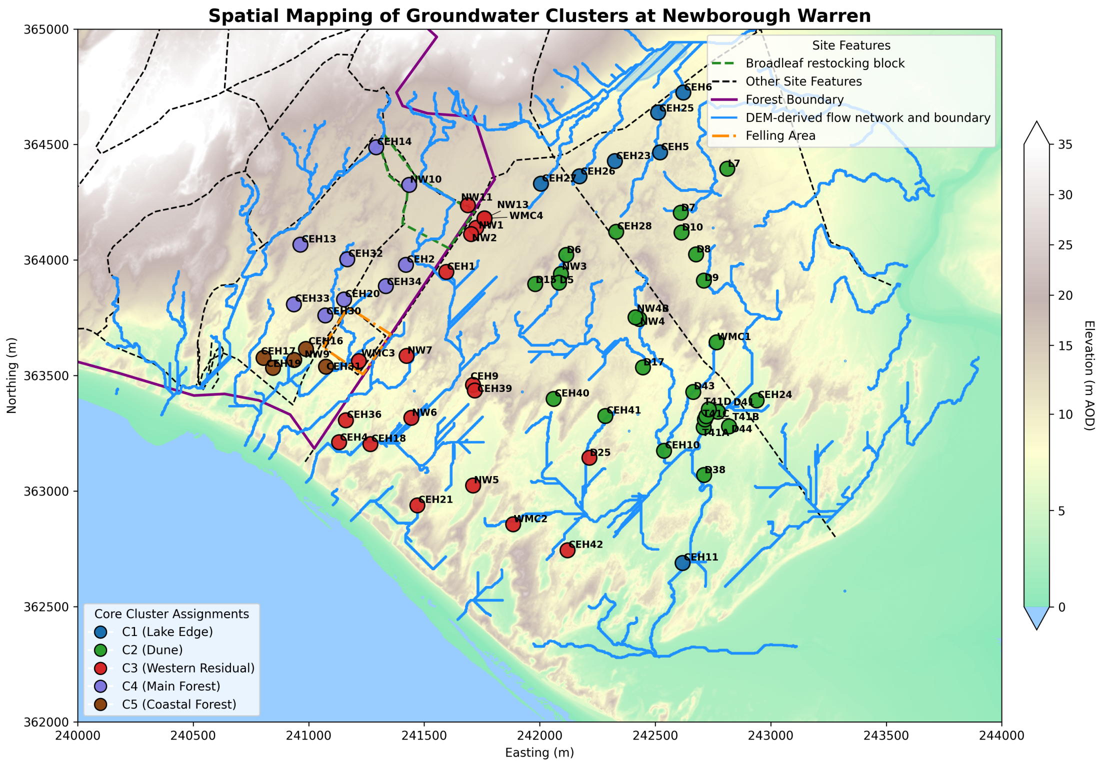

Figure 3. Spatial mapping of the five groundwater clusters identified by the analysis. Each colour represents a zone with distinct behaviour: C1 Lake Edge (blue), C2 Dune (green), C3 Western Residual (red), C4 Main Forest (purple), C5 Coastal Forest (brown).

How the five zones compare

The table below summarises the key characteristics of each groundwater zone. The ‘recharge sensitivity’ measures how strongly rainfall raises the water table; the ‘evaporation draw’ measures how strongly summer heat lowers it; the ‘drainage rate’ measures how quickly water drains away; and the ‘canopy share’ measures how much of the rainfall energy budget is consumed by evaporation from the canopy and soil rather than reaching the water table. All three coefficients are dimensionless model parameters — larger values mean a stronger effect.

Zone	Character	Recharge sensitivity (dimensionless)	Evaporation draw (dimensionless)	Drainage rate (month^{-1})	Canopy share (%)
C1 Lake Edge	Shallow, fast-draining, near tipping point	4.58 (highest)	0.96 (lowest)	0.090 (fastest)	22%
C2 Dune	Open mature dune, moderate response	3.87	1.74	0.063	26%
C3 Western	Deep buffer, slow response	3.58	1.81	0.060	28%
C4 Main Forest	Pine on thin substrate over bedrock	2.52 (lowest)	2.50 (highest)	0.021 (slowest)	40%
C5 Coastal Forest	Pine on deeper coastal sand; steepest decline	2.44	1.37	0.045	41%

Table 1. Summary of the five groundwater zones. Higher recharge sensitivity means stronger water table response to rainfall. Higher evaporation draw means more severe summer drying. Higher canopy share means more rainfall intercepted by trees.

The central finding: summer is what matters

Conventional thinking assumes that winter rainfall is what fills dune slacks. This study found the opposite: it is the *summer minimum* water level that determines whether a slack will flood the following winter. If the water table drops too low during summer, no realistic amount of winter rain can refill the deficit.

This matters because summers are getting warmer. Since 2013, summer temperatures at the site have been nearly 1°C above the long-term average, increasing evaporation and deepening the summer drought.

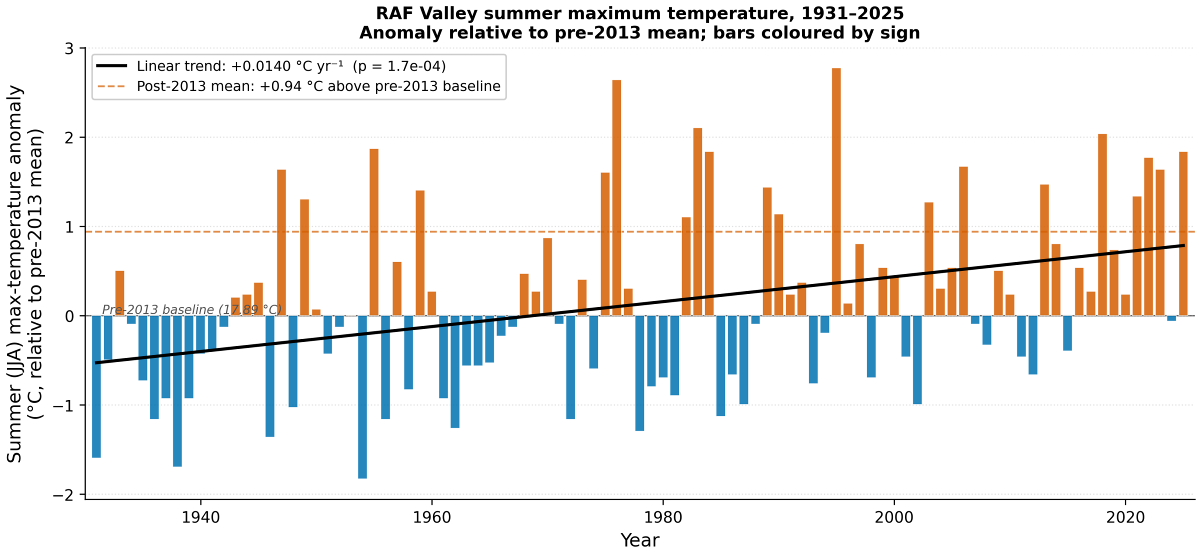

Figure 4. Summer temperature anomaly at RAF Valley (nearest weather station), 1931–2025. Orange bars show years warmer than the pre-2013 average; blue bars show cooler years. The dashed orange line marks the post-2013 mean: +0.94°C above baseline.

The water table has been declining at all five zones, with the trend most acute at the Lake Edge and Coastal Forest zones. At current rates of decline, the Lake Edge zone — where many of the most ecologically valuable slacks are located — is projected to cross the threshold for viable dune slack habitat around **2030–2032**.

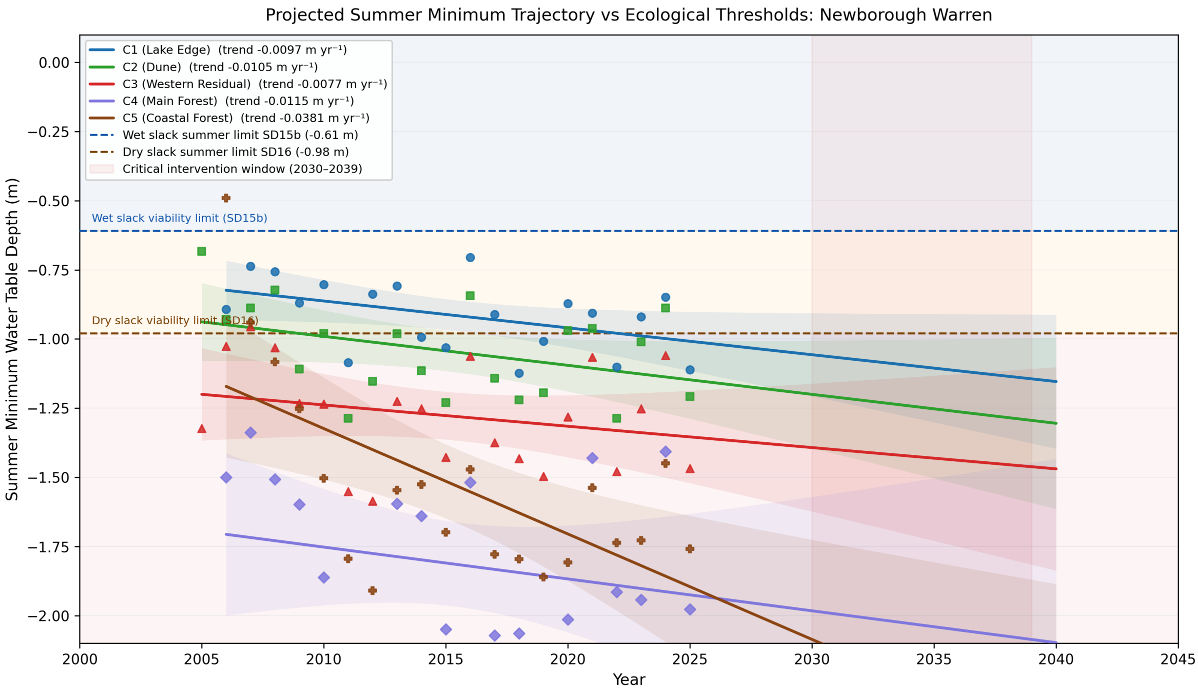

Figure 5. Projected summer minimum water table depth for all five clusters. The blue dashed line marks the wet slack threshold (–0.61 m); the brown dashed line marks the dry slack threshold (–0.98 m). The shaded yellow band highlights the critical intervention window (2030–2039). All clusters are tracking downward.

What management has been tried

Dune scraping

Dune scraping involves mechanically removing the top layer of sand to bring the ground surface closer to the water table. At one well (CEH36), three independent methods converged on a scraping benefit of 80–140 mm, with a paired summer minimum shift of +195 mm — more than half of the critical 37 cm ecological gradient. The benefit is geometric (a permanent lowering of the ground surface), retaining approximately 68% of the scrape depth as a long-term improvement.

However, scraping only works where it is placed correctly within the landscape. At more coastal locations (CEH18 and CEH21), the benefit was overwhelmed by a separate problem: the coastline itself is retreating, which lowers the water table from the seaward edge inward.

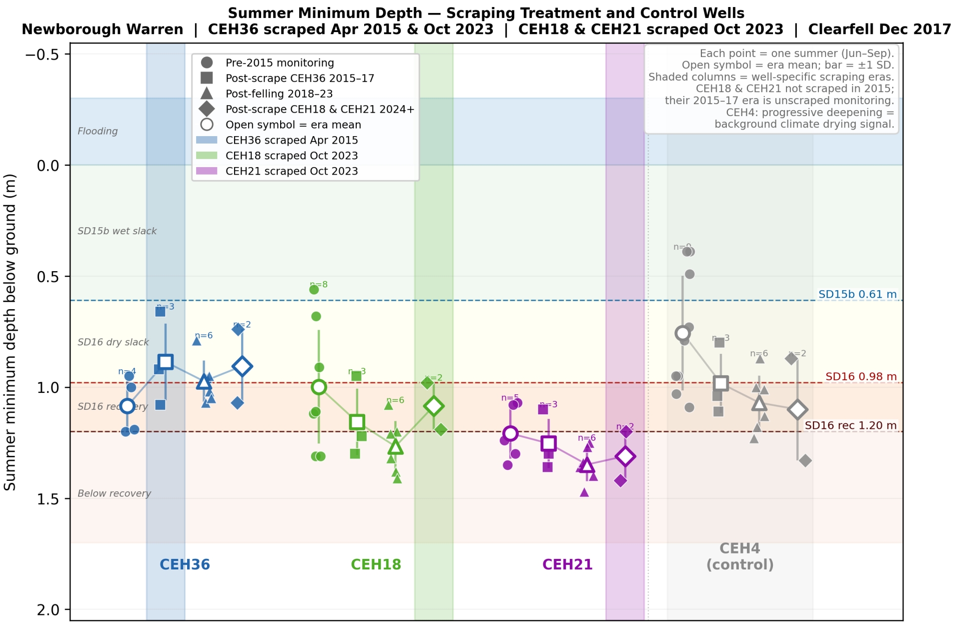

Figure 6. Summer minimum depth at the three scraped wells and a control (CEH4). CEH36 (blue) shows a clear upward shift after scraping in 2015. CEH18 and CEH21 (green and purple) scraped in 2023 show limited response. CEH4 (grey) demonstrates the background climate drying trend affecting all unmanaged wells.

The study recommends targeting scraping at inland transitional sites in the C1, C2 and C3 zones where the aquifer base is stable and the rainfall thresholds for winter flooding are still achievable.

Tree felling

In December 2017, approximately 8 hectares of Corsican pine were clearfelled as a management experiment. The study used a rigorous five-tier experimental design with 17 wells and three independent control groups to test whether removing the trees raised the water table.

The result was nuanced. Comparing felled wells against unfelled forest — the most direct test — the analysis detected a **statistically significant rise in mean monthly water levels** of around +93 mm at the core impact well and +153 mm at the forest edge. However, **summer**

minimum depths — the metric that determines whether dune slacks survive — showed no corresponding improvement. The clearfell raised average water levels but could not overcome the concurrent loss of recharge efficiency during the summer months when it matters most.

The analysis suggests the forest canopy acts as both a *sink* (intercepting rain) and a *buffer* (shielding the ground from direct evaporation in summer). Removing the canopy recovers some winter recharge but simultaneously exposes the soil to greater summer drying, and the two effects roughly cancel out.

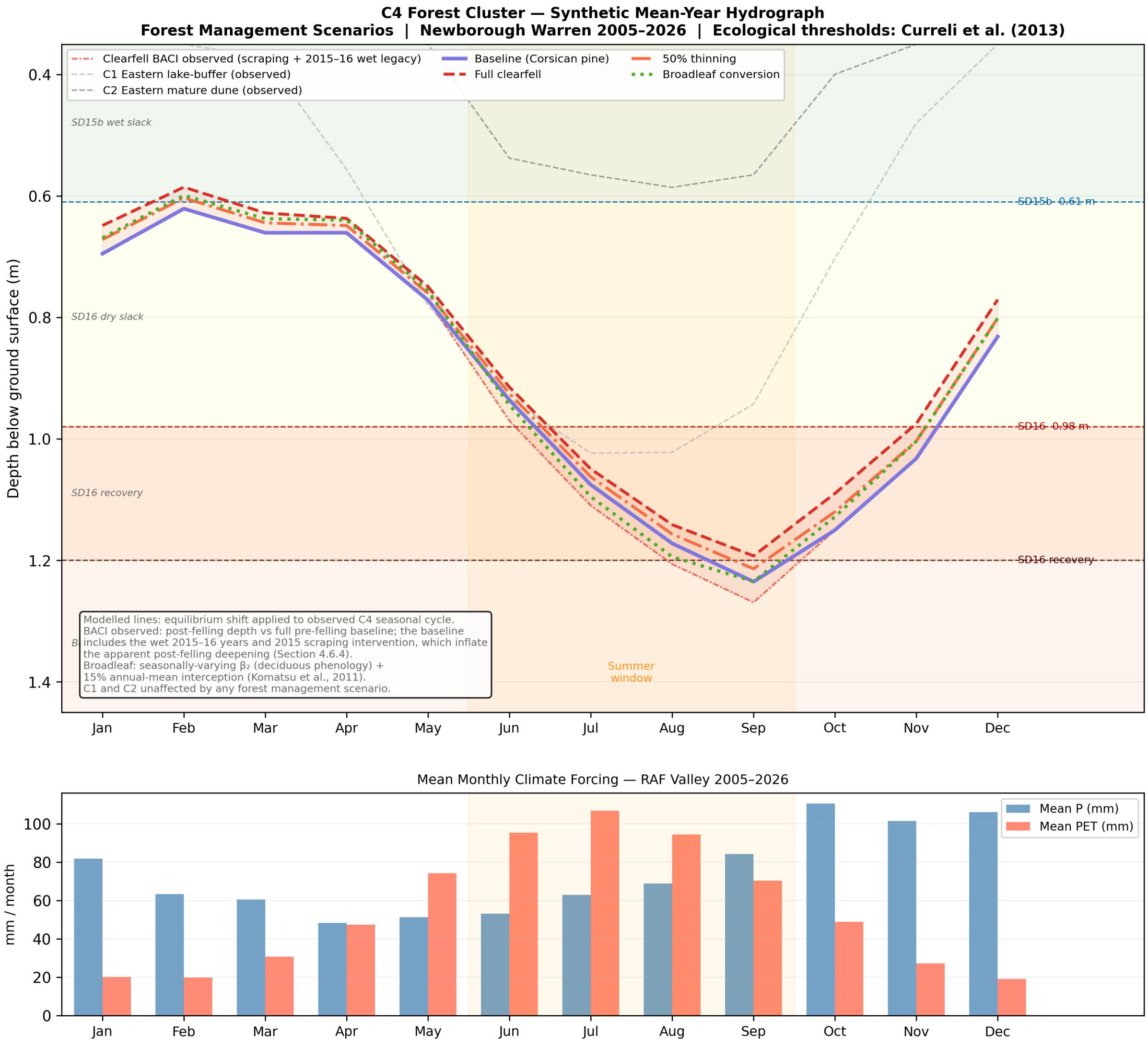

Figure 7. The seasonal water table cycle in the Main Forest zone (C4), showing the current baseline (blue) alongside modelled scenarios for full clearfell (red dashed), 50% thinning (orange) and broadleaf conversion (green dotted). The ecological threshold bands (wet slack, dry slack, recovery) are shown as coloured horizontal zones. The bottom panel shows the seasonal pattern of rainfall versus evaporation.

Crucially, changes to the forest do not propagate sideways to the open dune slacks where the ecological need is greatest. The forest and the open dunes operate as largely independent groundwater systems.

A declining recharge efficiency

Perhaps the most concerning finding is a site-wide decline in *recharge efficiency* — the proportion of rainfall that actually reaches the water table. This decline is the strongest candidate mechanism for the observed summer minimum deterioration across the entire monitoring network. It affects all five zones equally, regardless of whether they are forested or open, scraped or untouched, and operates independently of canopy cover. It is consistent with changing rainfall patterns (fewer sustained soaking events, more intense but brief storms that run off rather than infiltrating) and represents a climate-driven trend that no on-site management intervention can address.

Coastal erosion: a hidden and lagged threat

The coastline at Newborough is retreating. As the beach erodes, the aquifer loses volume at its seaward edge, and the water table adjusts downward. Because groundwater moves slowly through sand, the effects of coastal erosion take years to propagate inland — the aquifer's hydraulic response time is of the order of 7–13 years over typical distances. This means the decline visible in today's monitoring data reflects erosion that happened years ago. If erosion is accelerating, the worst effects have not yet arrived at interior wells.

Two control wells at different distances from the coast are both deteriorating in a pattern consistent with progressive coastal retreat, independently of any management action. Coastal-margin slacks may eventually require managed retreat rather than repeated restoration.

What this means for the future

The study's conclusions are sobering but clear:

1. **The window for effective intervention is finite** — measured in roughly one to two decades at the most vulnerable sites.
2. **Targeted dune scraping at carefully chosen inland sites** is the most effective direct intervention available, but its benefits are eroded over time by the background climate trend.
3. **Tree felling raises average water tables in the forest but does not improve summer minima** — the metric that determines dune slack survival. The evidence supports retaining forest cover while managing canopy density to partially recover the rainfall interception penalty without losing the summer buffering benefit. Forest management perturbations do not propagate to the open dune areas where habitat is most threatened.
4. **Climate change is the binding constraint.** Rising summer temperatures, declining recharge efficiency and coastal erosion are all operating in the same direction, and none can be addressed by on-site habitat management alone.
5. **Continued monitoring is essential.** The predictive tools developed in this study — including critical rainfall threshold equations and an interactive forecasting system — give site managers the ability to track whether conditions are on course to cross ecological thresholds, and to prioritise interventions where they can still make a difference.