

ACADEMIC SUMMARY

Hydrogeological Dynamics, Behavioural Clustering and Management Intervention Analysis at Newborough Warren Coastal Sand Dune Aquifer, Wales

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Based on: Newborough Warren Coastal Aquifer — Hydrogeological Analysis (161 pp.)

1. Introduction and Scope

This document summarises a 161-page hydrogeological analysis of Newborough Warren, a 1,300-hectare Special Area of Conservation (SAC) on the Isle of Anglesey, north-west Wales. The study presents the first network-wide, multi-method quantitative characterisation of groundwater behaviour at the site, integrating 89 wells across a 21-year monitoring record (April 2005 to February 2026).

The analytical pipeline comprises **26 scripted steps across eleven phases**, requiring only monthly dipwell readings and publicly available climate data from RAF Valley. It integrates hierarchical clustering, Pearson affinity analysis, a three-term state-space model (SSM), model benchmarking, water table fluctuation specific yield estimation, depth-dependent PET diagnostics, BACI intervention analyses, water balance decomposition, spatial coefficient mapping, critical rainfall threshold forecasting, seasonal prediction equations, and per-well scenario projections under UKCP18 climate and forest management scenarios. The framework is designed for replication at comparable coastal dune sites using minimal equipment.

2. Study Site

Newborough Warren is underlain by weakly permeable glacial till forming the effective base of the sand aquifer. A bedrock ridge runs south-west to north-east forming the northern boundary. The dune field is divided into an eastern block (shallower sand over till, responsive water table) and a western block (deep sand, buffered fluctuations). The northern 700 hectares are afforested with mature Corsican pine (*Pinus nigra* var. *laricio*), planted 1948–1965. Conservation management includes an experimental clearfell of ~8.4 ha commenced December 2017 and dune scraping at CEH36 (April 2015), CEH18 and CEH21 (October 2023). The dune slack communities (SD15b wet slack, SD16 dry slack) have eco-hydrological viability thresholds established by Curreli et al. (2013): SD15b requires summer minima shallower than -0.61 m; SD16 tolerates summer minima to -0.98 m. The entire ecological gradient spans only 37 cm of summer minimum depth.

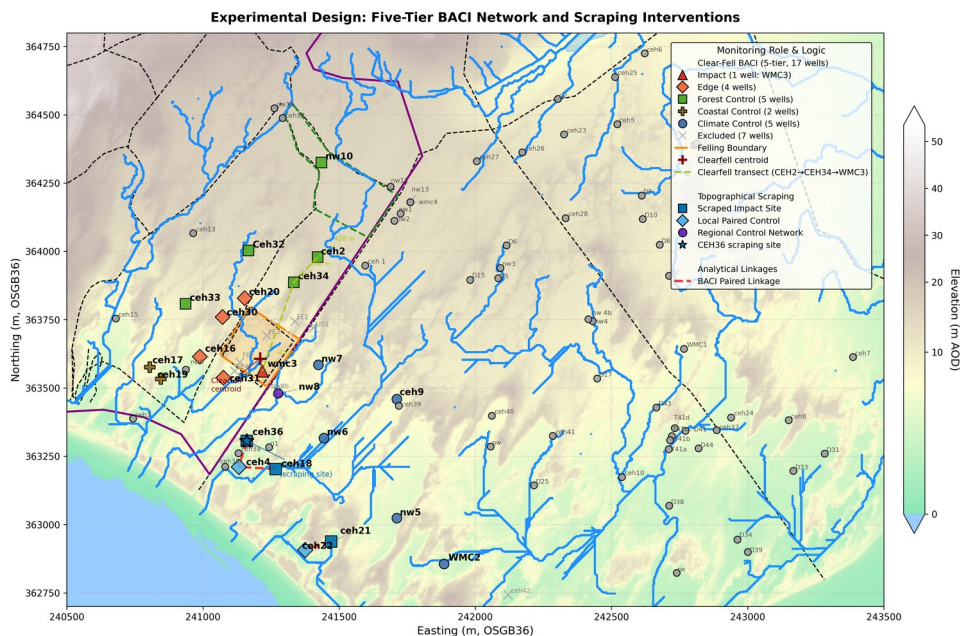


Figure 1. Experimental design: five-tier BACI network (Impact, Edge, Forest Control, Coastal Control, Climate Control) and scraping interventions. Source: 13_01_experimental_setup_map.png.

3. Methods Overview

Data sources. Groundwater levels from 89 dipwells, quality-controlled and bucketed to monthly timestamps by field convention. A reference network of 66 wells with >100 months of valid record formed the basis for clustering and SSM analyses. Monthly rainfall and Thornthwaite PET from RAF Valley (~16 km north; mean annual rainfall 890 mm, 2006–2025).

State-space model. The core mechanistic model is a three-term water balance equation fitted independently at each well: $\Delta h(t) = \beta_1 \cdot P(t) + \beta_2 \cdot (-PET(t)) + \beta_3 \cdot (-h_disp_prev(t))$. Each month, the change in water level is explained by three competing forces: rainfall pushing the water table up (β_1 , recharge sensitivity), evaporation pulling it down (β_2 , atmospheric draw), and drainage carrying water sideways towards the coast or lake (β_3 , head-dependent drainage). The displacement formulation ($h_disp = 3.7 + h_depth$) ensures physically correct parameterisation. The drainage term encodes the aquifer's memory: it is the explicit representation of head-dependent drainage that prevents the model from drifting in autonomous forecasting mode.

Clustering. Ward's minimum variance linkage on correlation-based dissimilarity ($k = 5$), extended to 89 wells via Pearson affinity analysis.

Seasonal prediction equations. Alongside the monthly SSM, paired seasonal prediction equations were fitted for each cluster. A winter equation predicts peak winter water level from cumulative winter rainfall (October–March) and the preceding summer minimum. A summer equation predicts summer minimum from cumulative summer rainfall (April–September) and the preceding winter peak. Together these capture the aquifer's memory: antecedent summer minimum depth, not winter rainfall, is the dominant predictor of winter flooding potential in the western and forest clusters.

Critical rainfall thresholds. Because the SSM is a physical mass balance, it can be run forwards: given a measured summer water level and a forecast of winter rainfall, it calculates whether the water table will rise high enough to flood a given slack. This produces a critical rainfall threshold (P_flood) for each well — the cumulative winter rainfall required to achieve flooding, expressed as a multiplier λ of the long-term climatological total. Wells where λ exceeds 2.0 are classified as structurally unreachable under any winter in the 95-year rainfall record.

Interventions. Scraping: two-tier CUSUM-BACI with synthetic control and SSM forward residual validation. Clearfell: three-counterfactual ANCOVA-BACI across 17 wells in a five-tier design, with cumulative water balance covariate, distance-weighted scraping covariate, $CWB \times clearfell$ interaction, and easting \times time coastal erosion interaction.

4. Key Results

4.1 Five Hydrogeological Clusters

Clustering identified five hydrogeologically distinct units spanning a behavioural spectrum from “shallow pan” to “deep sponge” to “canopy sponge”. Within the forest zone, elevation alone explains 95% of the variance in β_2 , confirming that substrate position rather than canopy structure drives the atmospheric draw coefficient. The primary binary split separates eastern till-influenced clusters (C1, C2) from western sand and forest clusters (C3, C4, C5).

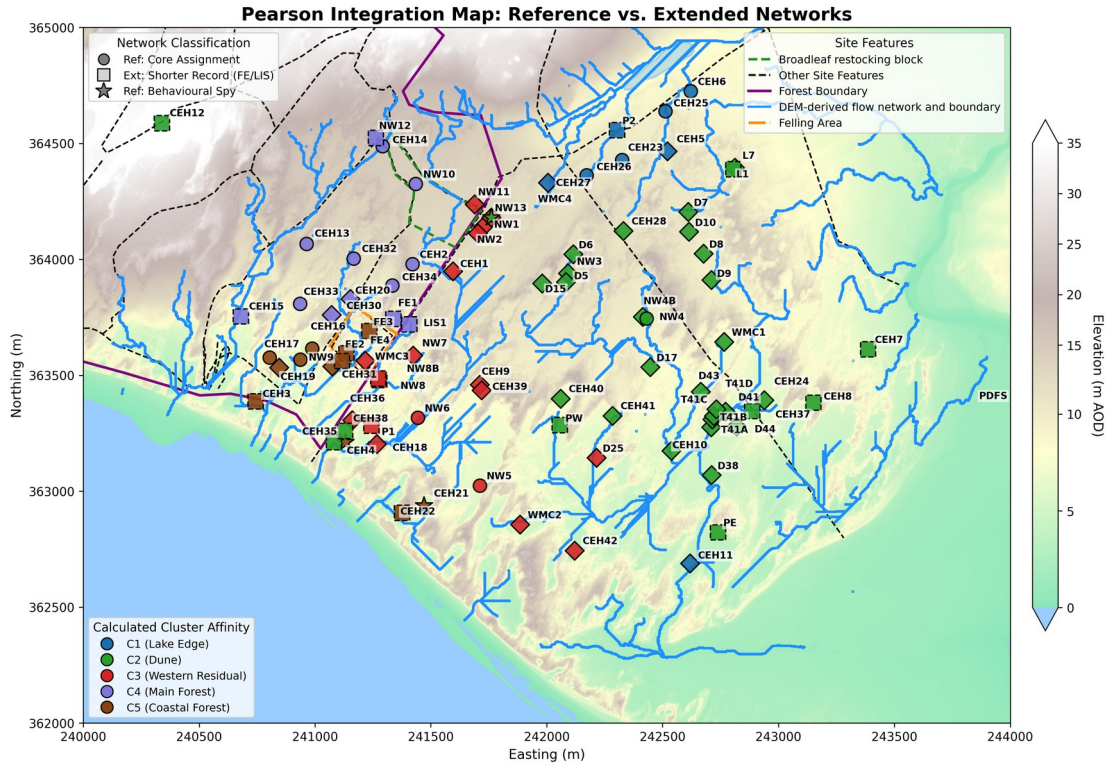


Figure 2. Pearson integration map: all 89 wells classified by cluster affinity across reference and extended networks. Source: 06_pear_02_integration_map.png.

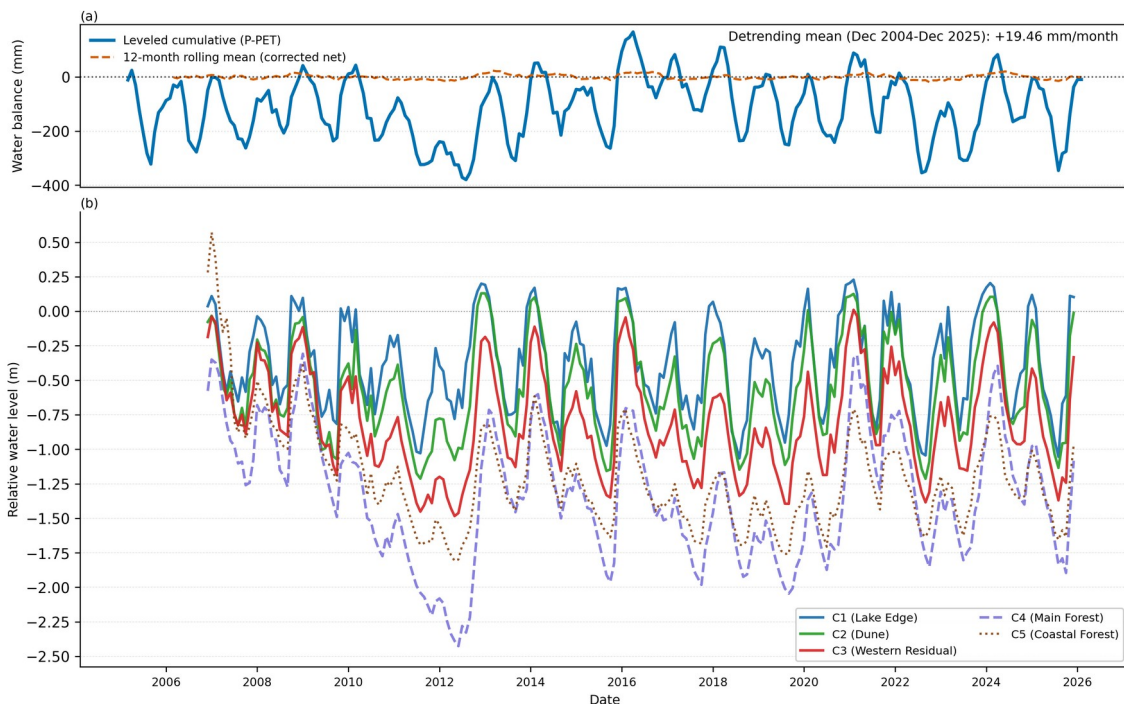


Figure 3. Cluster-mean water level hydrographs (b) and levelled cumulative water balance (a), 2005–2026. Source: 02_03_cluster_hydrographs_wb.png.

Table 1. Summary of the five hydrogeological clusters.

Zone	Character	Recharge sensitivity	Evaporation draw	Drainage rate	Canopy share	R ²
C1	Shallow, fast-draining, near tipping point	4.58 (highest)	0.96 (lowest)	0.090 (fastest)	22%	0.73
C2	Open mature dune, moderate response	3.87	1.74	0.063	26%	0.75
C3	Deep buffer, slow response	3.58	1.81	0.060	28%	0.81
C4	Pine on thin substrate over bedrock	2.52 (lowest)	2.50 (highest)	0.021 (slowest)	40%	0.68
C5	Pine on deeper coastal sand; steepest decline	2.44	1.37	0.045	41%	0.70

Recharge sensitivity (β_1), evaporation draw (β_2) and drainage rate ($-\beta_3$) are dimensionless SSM coefficients. Canopy share = $LCSC = 100/\beta_1$ (% of rainfall energy budget consumed by canopy/soil evaporation). All coefficients significant at $p < 0.01$.

4.2 Water Balance

The three-term SSM closes the water balance to within 2.5% at all clusters. Drainage accounts for 85% of losses at C1 (lake exchange) but only 26% at C4 where atmospheric draw dominates. The residual field is spatially structured, with positive residuals along the northern forest margin whose mechanistic attribution is unresolved — two independent diagnostic tests returned null results.

Table 2 (report Table 3a). Mean monthly head-space water balance (m/month).

Cluster	Label	Recharge	Atm. Draw	Drainage	Total Loss	Residual
C1	Lake Edge	0.341	0.053	0.292	0.345	-0.004
C2	Dune	0.288	0.095	0.196	0.291	-0.004
C3	Western Residual	0.266	0.099	0.167	0.266	0.000
C4	Main Forest	0.187	0.138	0.048	0.186	+0.002
C5	Coastal Forest	0.181	0.075	0.110	0.185	-0.004

All clusters receive identical forcing: mean $P = 74.4$ mm/month, mean $PET = 55.1$ mm/month.

4.3 Model Benchmarking and Forecasting Skill

The SSM was benchmarked against a Traditional Linear Model (TLM) that lacks the drainage feedback term. In one-step diagnostic mode both models perform near-identically (median $R^2 = 0.91$ vs 0.92), but in iterative forecasting — where the model runs forward using only climate data and its own predictions — the SSM achieved a **median iterative NSE of 0.76** versus **0.14 for the TLM** (+0.62 improvement). At individual wells the contrast can be dramatic: at CEH6 (Dune cluster), the SSM maintains realistic seasonal cycles in iterative mode (NSE = 0.66) while the TLM diverges progressively (NSE = -1.1). Positive iterative NSE was returned at 65/66 wells (SSM) vs 42/66 (TLM). The drainage term is what prevents the model from drifting.

Table 3 (report Table 4). Model benchmarking summary.

Metric	TLM	SSM	Δ
Median one-step R^2	0.91	0.92	+0.01
Median iterative NSE	0.14	0.76	+0.62
Wells with NSE > 0	42 / 66	65 / 66	—
Max improvement (CEH25)	-1.47	0.68	+2.15

Iterative NSE over 100 months without observational correction.

4.4 Seasonal Prediction and Critical Rainfall Thresholds

The seasonal prediction equations establish that **antecedent summer minimum depth, not winter rainfall, is the dominant predictor of winter flooding potential** in the western and forest clusters. If the water table drops too low during summer, no realistic amount of winter rain can refill the deficit. As a worked example, the Eastern Block summer equation is: Summer minimum = $0.0016 \times P_{\text{summer}} + 0.51 \times h_{\text{winter_peak}} - 1.57$ ($R^2 = 0.63$). For every additional 100 mm of summer rain the summer minimum is 0.16 m shallower; for every 0.10 m higher winter peak the summer minimum is 0.05 m shallower. The intercept (-1.57 m) represents the structural deficit.

The P_{flood} threshold equations reduce to a linear form $P_{\text{flood}} = A \cdot d + B$ for each cluster, where d is summer minimum depth and P_{flood} is cumulative winter rainfall required. The slope A rises from 167 mm/m

at C1 through 215 (C2), 230 (C3) to 355 (C5) and 371 (C4), reflecting progressively greater marginal rainfall demand per unit of summer drawdown. Wells where the rainfall multiplier λ exceeds 2.0 are structurally unreachable under any winter in the 95-year record. These equations and the scenario framework are implemented as interactive web tools hosted on the project page.

Table 4 (report Table 15). Cluster-specific critical rainfall threshold equations.

Cluster	Label	Horizon	$P_{\text{flood}} = A \cdot d + B$	ΣP_{clim}
C1	Lake Edge	Oct–Feb (5 mo)	$167.2 \cdot d + 398.6$	464 mm
C2	Dune	Oct–Feb (5 mo)	$215.0 \cdot d + 367.2$	464 mm
C3	Western Residual	Oct–Mar (6 mo)	$229.7 \cdot d + 463.0$	524 mm
C4	Main Forest	Oct–Mar (6 mo)	$370.9 \cdot d + 356.4$	524 mm
C5	Coastal Forest	Oct–Mar (6 mo)	$354.7 \cdot d + 509.9$	524 mm

d = observed summer minimum depth (m, positive below ground). *P_{flood}* = cumulative winter rainfall (mm) over the cluster's recharge horizon. $\lambda = P_{\text{flood}} / \Sigma P_{\text{clim}}$; $\lambda > 1.0$ requires above-average winter rainfall.

4.5 Dune Scraping

Scraping at CEH36 produced a **paired summer minimum shift of +195 mm** ($p = 0.004$) — more than half the 37 cm SD15b–SD16 ecological gradient. Three independent methods converged: raw BACI +131 mm, synthetic control +135 mm, SSM forward residual +83 mm. The benefit is geometric (permanent surface lowering), retaining ~68% of scrape depth long-term, and persisted through the post-felling period while the paired control deteriorated.

CEH18 and CEH21 (scraped October 2023) showed limited responses that did not survive climate correction — consistent with coastal boundary retreat overwhelming the intervention. No detectable drawdown was found uphill ($p = 0.54$), though the observation window is too short to rule out longer-timescale propagation. Because scraping operates through the same mechanism as coastal erosion, its placement within the drainage system determines whether it complements or exacerbates existing coastal drainage. The study recommends targeting scraping at inland transitional sites in C1/C2/C3 where the aquifer base is stable and *P_{flood}* thresholds remain achievable ($\lambda < 1.5$).

4.6 Clearfell Experiment

The December 2017 clearfell of 8.4 ha was tested using a five-tier, 17-well BACI experiment. Against the Forest control — comparing felled wells against unfelled forest sharing the same canopy and substrate — the ANCOVA-BACI detected a **significant clearfell step of +93 mm at Impact ($p = 0.019$) and +153 mm at Edge ($p < 0.001$)**, confirmed by synthetic extension of within-compartment FE wells (+103 mm, $p = 0.011$). The CWB × clearfell interaction was non-significant, indicating that canopy removal raised mean water levels without altering the system's sensitivity to climate forcing.

However, **summer minima analysis found no corresponding improvement**. The mixed-effects model found no significant clearfell effect at Impact (WMC3: -30 mm, $p = 0.76$), and the pooled Edge result was significant but **in the opposite direction** (-72 mm, $p = 0.031$). The forest canopy appears to act 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. A **site-wide decline in recharge efficiency (β_1)** across all five BACI tiers — independent of management intervention and consistent with changing rainfall intensity or seasonality — is the strongest candidate for the observed summer minimum deterioration.

Table 5 (report Table 7). Three-counterfactual ANCOVA-BACI clearfell results.

Control	Zone	Step (m)	95% CI	p	Sig
Forest	Impact	+0.093	[+0.016, +0.170]	0.019	*
Forest	Edge	+0.153	[+0.090, +0.216]	<0.001	***
Climate	Impact	+0.050	[-0.002, +0.102]	0.060	ns
Climate	Edge	+0.238	[+0.126, +0.350]	<0.001	***
Combined	Impact	+0.063	[+0.024, +0.103]	0.002	**
Combined	Edge	+0.194	[+0.121, +0.266]	<0.001	***

Forest control is the most direct test. Climate/Combined controls conflate the clearfell signal with the forest-vs-open divergence and coastal erosion gradient.

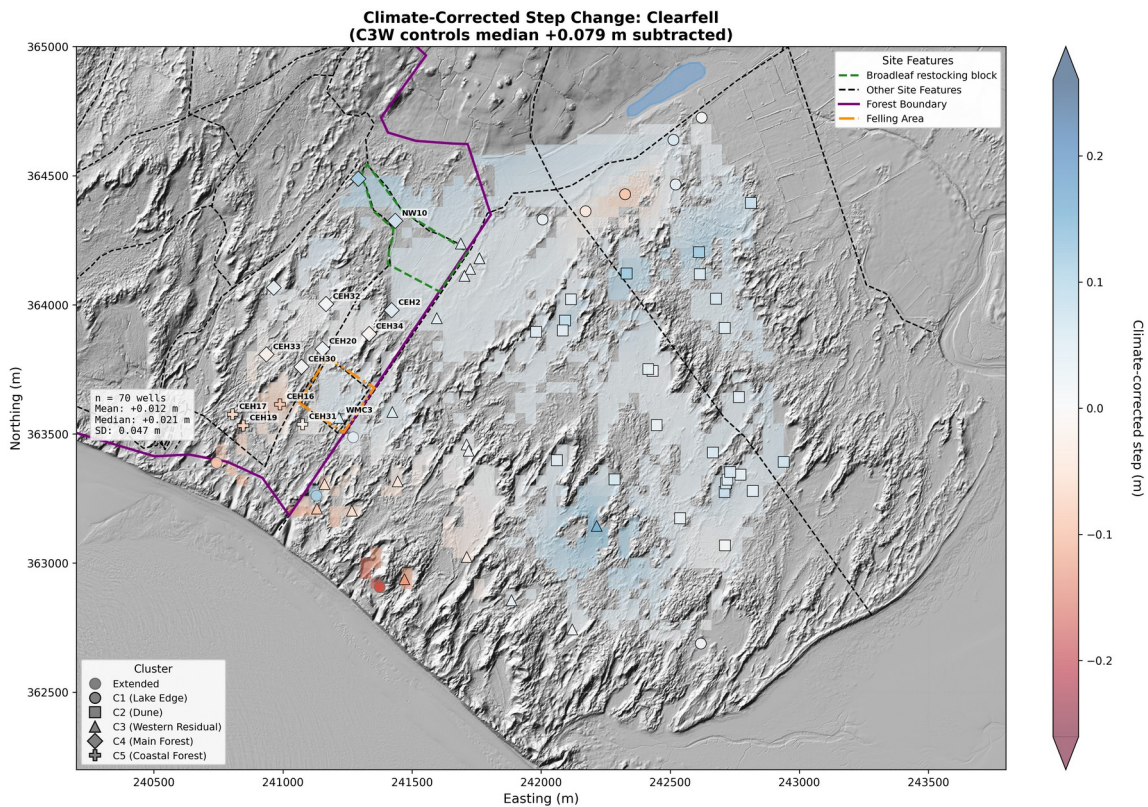


Figure 4. Climate-corrected spatial step change at the clearfell (C3W controls median subtracted). Source: 10b_spatial_fell_corrected.png.

4.7 Forest Management Scenarios and Broadleaf Conversion

Dipwell NW10 within a broadleaf block (established 1993–96) shows higher recharge sensitivity ($\beta_1 = 3.526$ vs C4 median 2.338), consistent with deciduous canopy intercepting less winter rainfall. Its summer minimum sits +247 mm shallower than adjacent pine wells on average, but this advantage is **diminishing at -46 mm/yr** ($p = 0.024$) as canopy closure increases. The stand was characterised by dense bramble understorey throughout most of the monitoring period, with fewer than four years of post-closure record.

The scenario framework predicts modest positive annual responses to clearfell and thinning at the forest clusters (**clearfell: C4 +4.7 mm w.e./month, C5 +8.8 mm; thinning: C4 +2.3, C5 +4.4**), driven primarily by winter recharge gain. Broadleaf conversion is near-neutral (**C4 -3.4 mm; C5 +0.1 mm**): the modest interception reduction (24% to 15%) is consumed by growing-season transpiration and lost through rapid drainage before summer. These magnitudes are **substantially smaller than climate-driven changes** (C4 dry-scenario -15.2 mm; wet-scenario +7.5 mm). Forest management perturbations do not meaningfully propagate to C1/C2 where ecological need is greatest.

4.8 Climate Trajectory and Threshold Exceedance

Summer minima declined at all clusters: C1 -0.0097 m/yr ($p = 0.048$), C2 -0.0105 ($p = 0.084$, marginal), C3 -0.0077 (ns), C4 -0.0115 (ns), and **C5 -0.0381 m/yr ($p = 0.003$)** — $3.9\times$ any other cluster. C5 is the only cluster with a significant winter decline (-0.037 m/yr, $p = 0.035$). The post-2018 collapse in C5 seasonal amplitude (-18% raw, -21% climate-normalised) suggests at least one site-specific structural process beyond the common climate signal. Post-2013 summer temperatures have run $+0.94^\circ\text{C}$ above the long-term baseline.

C1 exceeded the wet slack winter flooding threshold (-0.10 m) in **14/20 years (70%)**; C2 in 11/21 (52%); C3 in 1/21 (5%); C4 never; C5 in 1/20 (5%). C1 has remained below the wet slack summer threshold in all 20 monitored years. Trend extrapolations indicate C1 summer minima approaching the **SD16 threshold around 2030–2032**.

Projected Climate Trajectory vs Ecological/Flooding Thresholds: Newborough Warren

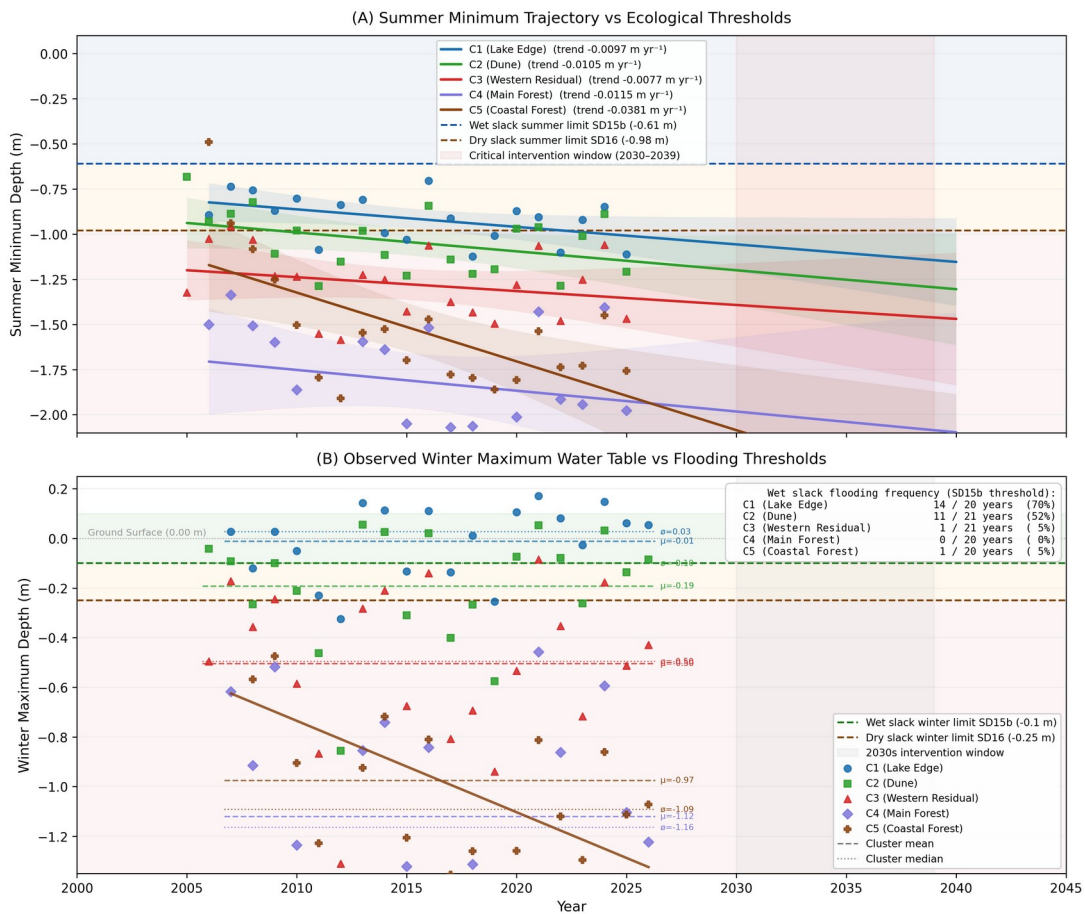


Figure 5. Climate trajectory vs ecological thresholds. (A) Summer minimum trends with critical intervention window 2030–2039. (B) Winter maximum flooding record with exceedance frequencies. Source: 14_climate_trajectory_stacked.png.

4.9 Spatial Distribution of Summer Minima and Flooding

Only 5 of 87 wells (6%) currently sit above the SD15b wet slack viability threshold. A further 11 (13%) are within shallow excavation range (0.61–0.75 m), and 30 (34%) in the SD16 dry slack zone. Twenty-five wells (29%) are beyond standard single scraping reach (>1.2 m). Winter flooding frequency shows a stark spatial contrast: the eastern C1/C2 zone floods in >50% of years, while forest and western zones rarely or never flood.

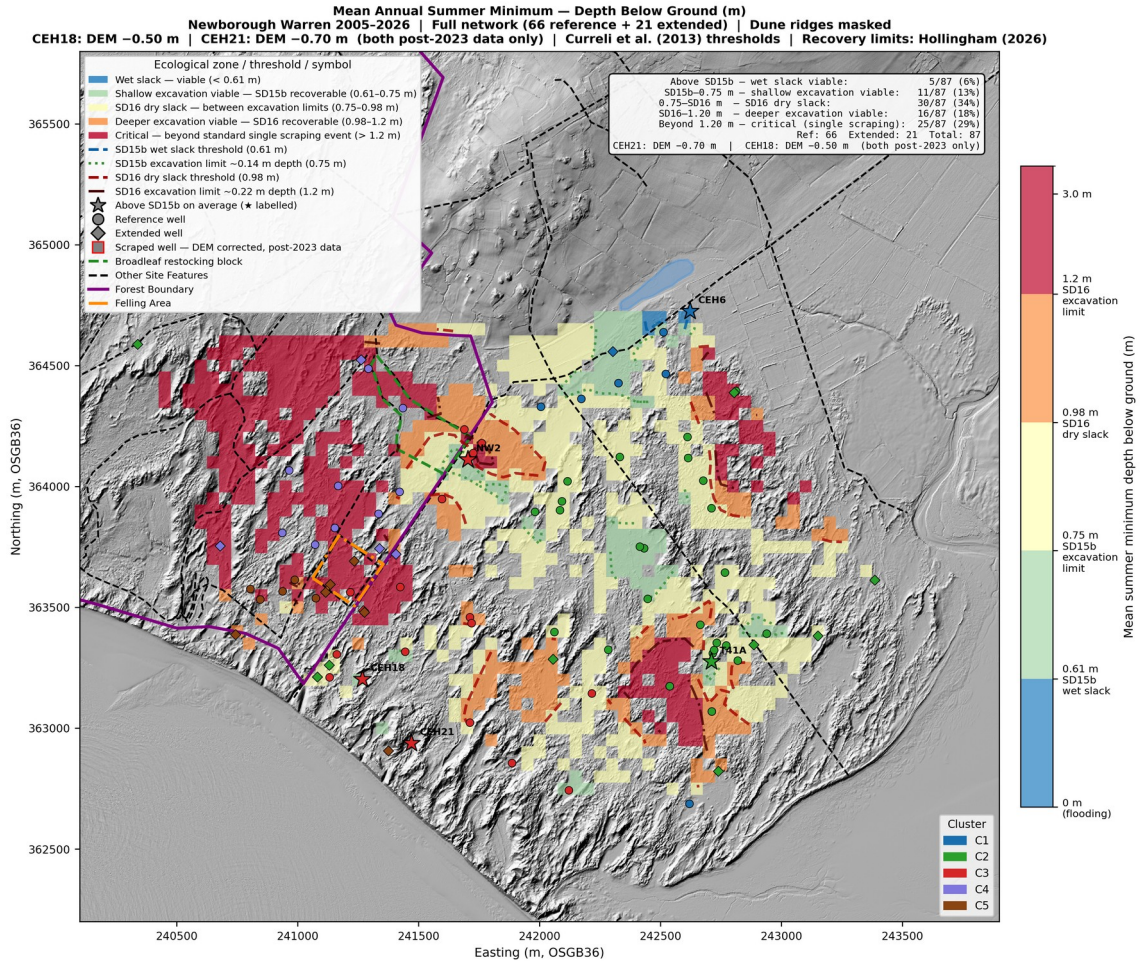


Figure 6. Mean annual summer minimum depth below ground, classified against Curreli et al. (2013) thresholds and scraping recovery limits. Source: 11b_01_summer_minima_depth.png.

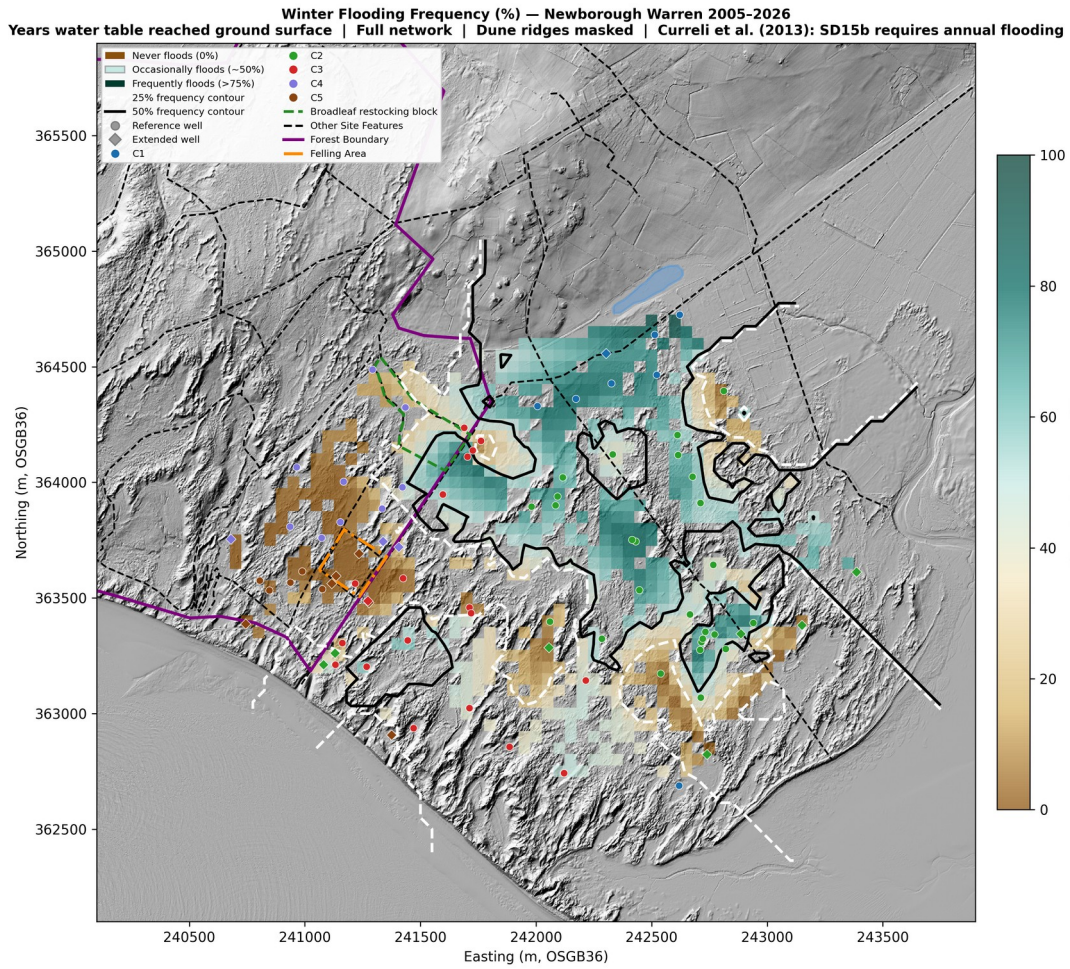


Figure 7. Winter flooding frequency (% of years water table reached ground surface), 2005–2026. Source: 11b_04_flood_frequency.png.

5. Principal Conclusions

The report's twelve conclusions can be grouped into four themes:

Aquifer architecture and forecasting. Five clusters govern site hydrology. The SSM outperforms the TLM by +0.62 median NSE, with the drainage feedback term essential for preventing model drift in autonomous forecasting. WTF-derived specific yields converge across all clusters once interception is corrected. The water balance closes to within 2.5%. Seasonal prediction equations establish that summer minimum depth, not winter rainfall, is the dominant predictor of winter flooding potential. The P_{flood} threshold equations provide an operational tool for targeting interventions where λ remains achievable.

Management interventions — scraping. Scraping at CEH36 delivered +195 mm summer minimum benefit ($p = 0.004$), spatially confined and placement-critical. Priority targets are C1/C2/C3 transitional wells where the aquifer base is stable and $\lambda < 1.5$. CEH21's failure to respond confirms that position within the coastal drainage pathway determines efficacy.

Management interventions — clearfell. The clearfell produced a statistically significant mean monthly recovery against the Forest control (+93 mm Impact, +153 mm Edge), but this recovery **did not translate into improved summer minima** — the ecologically critical metric. The mixed-effects Edge result was significant in the opposite direction (−72 mm, $p = 0.031$). A site-wide β_1 decline affects all BACI tiers equally and is the strongest candidate for summer minimum deterioration, operating independently of canopy cover. The scenario framework predicts modest clearfell/thinning responses at C4/C5, all substantially smaller than climate-driven changes. The evidence supports retaining forest cover while managing canopy density to partially recover the interception penalty without losing the summer buffering benefit. Forest management perturbations do not propagate to C1/C2.

Climate trajectory and the intervention window. C1 approaches SD16 around 2030–2032. C5 shows the steepest decline in both seasons ($3.9\times$ C1). Rising summer temperatures, declining recharge efficiency and coastal erosion are all operating in the same direction. Progressive coastal boundary retreat is an independent, potentially accelerating threat with lagged consequences (hydraulic diffusivity $L^2\text{Sy}/K$ of order 7–13 years). The operational domain for intervention is **targeted scraping in C1/C2** combined with canopy density management. **The intervention window is one to two decades.**

6. Limitations

Eight principal limitations are identified: (1) monthly temporal resolution underestimates event-scale volatility; (2) Thornthwaite PET may overestimate demand by 10–15% vs Penman-Monteith — absolute P_{flood} thresholds are conservative upper bounds, though relative rankings and spatial patterns are unaffected; (3) the NW10 broadleaf comparison relies on a single well with positional confounders, complicated by dense bramble understorey and fewer than four years of post-closure record; (4) the spatial framework is a per-well SSM aggregator, not a calibrated continuous-flow model; (5) the monitoring network was not purpose-built as a propagation transect, limiting spatial resolution <100 m from the clearfell edge; (6) neither intervention analysis explicitly models the multi-year to multi-decadal propagation timescale of coastal erosion signals; (7) the water balance residual field is spatially structured but mechanistically unresolved; (8) surface topography is a co-determined proxy for subsurface structure mediated by glacial till, bedrock and aeolian deflation processes.

7. Citation

Hollingham, M. (2026). Hydrogeological Dynamics, Behavioural Clustering and Management Intervention Analysis at Newborough Warren Coastal Sand Dune Aquifer, Wales. Draft manuscript, March 2026. 161 pp.

Repository: https://github.com/newbroman/Newborough_Hydrology

Web tools: https://newbroman.github.io/Newborough_Hydrology