

Annual simulated hydrological contrasts and SWAT+ parameter sensitivity in a coastal mineral-sand mining basin of Madagascar

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Research Article

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Abstract

Attributing hydrological change to mining is difficult when only model outputs and a basin-internal reference are available. We tested whether annual baseline outputs from the Soil and Water Assessment Tool Plus (SWAT+) for Mandena, southeastern Madagascar, showed a post-2008 shift relative to an internal reference. A retrospective before–after–control–impact (BACI)-style comparison used area-weighted values from 216 mining-zone and 308 reference-zone hydrological response unit intersections over 1993–2022. For nine water-balance outputs, annual mining-minus-reference differences were regressed on a post-2008 indicator using Newey–West standard errors and Holm correction. No threshold-associated shift was detected (all adjusted $p = 1.000$). Percolation had the largest negative estimate (-5.46 mm yr^{-1}), but increased in both zones and varied widely among years. This result does not demonstrate the absence of mining effects or insufficient alteration of soil properties. In a separate sensitivity experiment, low-, intermediate- and high-magnitude parameter changes were imposed on vegetation, surface and soil terms in 158 selected mining-zone units. These changes redistributed simulated evapotranspiration, runoff, water yield and percolation, but do not establish that equivalent changes occurred historically. The study distinguishes temporal detection from model sensitivity and supports environmental monitoring that combines outputs at finer temporal resolution with discharge, piezometry and separate wetland observations.

Introduction

Tropical coastal basins combine strong climatic variability with short hydrological flow paths, sandy soils and wetlands [1–3]. Changes in rainfall and vegetation redistribute water among interception, plant transpiration, soil evaporation, surface runoff, percolation and soil-water storage [4–7]. In coastal areas where mineral-sand extraction occurs, these processes can respond to both land disturbance and regional climate variation [8,9].

Hydrological attribution is therefore difficult [10–13]. A before–after comparison restricted to the disturbed zone can conflate a local response with a basin-wide trajectory, whereas a parameterised disturbance scenario can demonstrate model sensitivity without showing that the same change occurred historically. Here, “basin-wide trajectory” means same-direction annual change in both zone outputs, not identical processes or absolute values. For environmental assessment, shared temporal change, zone-specific divergence and imposed model response must therefore be evaluated separately.

Before–after–control–impact (BACI) designs compare an affected zone with a reference zone before and after an intervention [10–14]. In this study, “BACI-style” denotes a retrospective breakpoint comparison of model outputs rather than a replicated field experiment. The relevant quantity is a difference in temporal change, not a direct comparison of absolute levels. A basin-internal reference can remove variation shared by both zones, although inference still depends on spatial support, temporal resolution, reference selection and data quality.

The Taolagnaro coastal basin in southeastern Madagascar provides a relevant case for testing whether annual outputs from a fixed mining-zone polygon diverged from those of a basin-internal reference after operations began [15–18]. Mandena contains sandy substrates, low relief, littoral wetlands, open water and contrasting vegetation types. QIT Madagascar Minerals began operations at Mandena in 2008, and first ilmenite production started in late 2008 [19–21]. We therefore use 2008 as the documented operational threshold for the annual comparison, not as evidence of an instantaneous hydrological break.

This study uses two separate analytical components. First, a mining-versus-reference retrospective BACI-style comparison evaluates area-weighted annual baseline outputs from the Soil and Water Assessment Tool Plus (SWAT+) over 1993–2022. Rainfall Estimates (RFE) from the Direction Générale de la Météorologie de Madagascar (DGM) cover 1993–2020, precipitation for 2021–2022 is infilled by the SWAT+ weather generator, and temperature comes from NASA POWER [22–27]. Annual values are aggregated from hydrological response units (HRUs), the model units defined by land cover, soil and slope. Second, low-, intermediate- and high-magnitude parameter-perturbation scenarios alter curve number, surface roughness, leaf area, biomass, residue cover and available water capacity in selected mining-zone HRUs [7,23,28]. These labels denote predefined magnitudes of imposed parameter change; they are not observed or calibrated levels of mining disturbance.

The study addresses two questions. First, do annual baseline SWAT+ outputs show a threshold-associated shift in the mining-zone-minus-reference difference after 2008? Second, how does SWAT+ redistribute the simulated water balance when low-, intermediate- and high-magnitude parameter changes are imposed on selected mining-zone HRUs? The first question addresses temporal detectability at the annual zonal scale. The second is a separate model-sensitivity experiment; it neither tests the temporal hypothesis nor establishes that corresponding parameter changes occurred at Mandena.

The hypothesis applies only to the mining-zone-versus-reference temporal comparison: if annual baseline outputs from the mining zone showed a distinct post-2008 level shift relative to reference-zone outputs, the post-2008 coefficient (β_1) would differ from zero for one or more of nine water-balance outputs. If both zones follow the same-direction annual pattern, β_1 should remain indistinguishable from zero. This estimand is a model-output contrast associated with the operational threshold, not a direct test of observed soil alteration or a causal estimate of mining effects.

Accordingly, the objectives are to (i) construct the two spatial supports and estimate post-2008 changes in nine annual mining-minus-reference output differences, with climate forcing reported separately as a diagnostic; and (ii) quantify the response of selected mining-zone HRUs to three predefined magnitudes of parameter perturbation. The first objective tests the stated temporal hypothesis. The second informs process interpretation only and is not combined with the temporal result as causal evidence.

Methods

Study area

The study focuses on the Mandena sector of the Taolagnaro coastal basin in southeastern Madagascar. The sector has sandy soils, littoral wetlands, open water and low relief [1,2,17]. No piezometric observations were available for this study; water-table depth was therefore not quantified, and no numerical claim about a shallow water table is made.

The year 2008 separates the pre-operational period 1993–2007 from the operational period 2008–2022 because QIT Madagascar Minerals began operations at Mandena in 2008 and first ilmenite production started in late 2008 [19–21]. At the annual time step, 2008 is treated as an operational-threshold year. This choice does not assume that land-cover, soil and hydrological changes occurred simultaneously throughout the fixed analytical footprint.

Spatial data

Spatial processing used the AW3D30 digital surface model, the basin boundary, the fixed analytical mining polygon Mine_Mandena.shp, SWAT + HRU polygons and the ESA WorldCover 2021 raster [29,30]. In this article, the “mining footprint” means only this fixed analytical polygon; it does not denote the area disturbed in each year or the full operational concession. WorldCover is a 10 m land-cover raster used to characterise classes inside that polygon and was not used as a substitute for its boundary. All areas, intersections and distances were calculated in EPSG:32738 (WGS 84 / UTM zone 38S; Fig. 1).

WorldCover classes inside the mining polygon were grouped as woody vegetation, herbaceous formations or crops, built-up or sparsely vegetated surfaces, and water or wetlands [30]. This characterisation documents the heterogeneous land-cover composition of the analytical footprint without changing its geometry.

Potential reference zones were generated as circular buffers centred on regularly spaced grid points within the available basin area. At each point, the buffer radius was calculated from the fixed mining-polygon area; circles extending beyond the available area were clipped. Median elevation was calculated as the median of all valid AW3D30 raster-cell elevations whose cell centres fell within each polygon; NoData cells were excluded. Candidate zones were ranked using the absolute difference in this median and the relative difference in area from the mining polygon. Compactness was recorded for audit but assigned zero weight. “Hydrological response series” means the annual SWAT+ output time series associated with a candidate zone; no such model-output series entered reference selection. The selected reference covered 1,379.7 ha, compared with 1,381.9 ha for the mining polygon, an area difference of 0.16%; both medians rounded to 9 m. The reference and mining zones intersected 308 and 216 HRUs, respectively. The circular geometry standardised the initial candidate area, while basin location, separation, area and elevation were assessed before outcome analysis. The selected reference is therefore a basin-internal spatial comparator rather than an experimental replicate [12–14].

SWAT+ model and simulation period

The water balance was simulated with the Soil and Water Assessment Tool Plus (SWAT+) at the hydrological response unit (HRU) scale [22–24]. An HRU is a model unit defined by a specific combination of land cover, soil and slope within the SWAT+ spatial structure; HRUs are not monitoring plots. The analysis uses annual and monthly HRU water-balance outputs, principally `hru_wb_yr` and `hru_wb_mon`.

No continuous local discharge series was available for strict streamflow calibration and validation over 1993–2022 [22,31]. The analysis therefore compares trajectories within the same model configuration and does not treat the simulated fluxes as observed discharge. This design can reduce shared model bias in relative contrasts, but it cannot substitute for hydrometric validation and does not reconstruct an observed history of disturbance.

The fixed mining polygon intersects 216 HRUs and the reference polygon intersects 308 HRUs. For every year, values of the nine tested outputs—percolation, water yield, generated surface runoff, mean soil water, final soil water, annual soil-water change, actual evapotranspiration, plant transpiration and soil evaporation—and the precipitation and potential-evapotranspiration diagnostics were aggregated within each zone. Each HRU value was multiplied by the area of its intersection with that zone, the products were summed, and the sum was divided by the total intersected HRU area. The effective supports were 1,103.9 ha for the mining zone and 1,341.5 ha for the reference zone, equivalent to 79.9% and 97.2% of their full polygon areas. The same intersections and weights were used in every year.

Climate data and potential evapotranspiration

Precipitation and temperature forcing came from two publicly accessible services. Daily precipitation for 1993–2020 came from the Rainfall Estimates (RFE) product of the Direction Générale de la Météorologie de Madagascar (DGM) Maproom / Madagascar Climate Data Library through its OPeNDAP service [26]. Daily minimum and maximum air temperature for 1993–2022 came from the National Aeronautics and Space Administration Prediction Of Worldwide Energy Resources (NASA POWER) service [32]. The files were converted to SWAT+ climate format.

The SWAT+ TxtInOut folders use `pcp_local.pcp` for the DGM RFE precipitation series and `tmp_local.tmp` for NASA POWER temperature. The years 2021 and 2022 contain precipitation generated within SWAT+ because the DGM RFE series ends in 2020. Their influence was evaluated as a sensitivity diagnostic and was not made a separate research objective.

Potential evapotranspiration was computed in SWAT+ with the code `PET = 1` in `codes.bsn` [23,25], corresponding to the Penman–Monteith method in the SWAT+ coding (0 = Priestley–Taylor, 1 = Penman–Monteith, 2 = Hargreaves, 3 = external read). The same setting was used for the baseline and for the low-, intermediate- and high-magnitude scenarios. Radiation, relative humidity and wind required

by Penman–Monteith but not supplied directly by the precipitation and temperature forcing files were generated within SWAT+ [25].

Precipitation and potential evapotranspiration (PET) were retained as forcing diagnostics [25,26]. Precipitation was used to verify the match of rainfall forcing between the mining and reference zones. PET was retained to document the hydrometeorological calculation associated with Penman–Monteith and was not interpreted as a mining response. The input datasets and their analytical roles are summarised in Table 1.

Table 1
Input data, sources and role in the SWAT+ BACI analysis

Data	Source	Resolution / period	Use in the study
AW3D30	JAXA	30 m	Topography, elevation, spatial support
ESA WorldCover 2021	Zanaga et al.	10 m	Land cover
SoilGrids 2.0	Poggio et al.	Soil raster	Soil classes and parameters
pcp_local.pcp	DGM Maproom / Madagascar Climate Data Library RFE	1993–2020 daily rainfall product	Precipitation forcing
tmp_local.tmp	NASA POWER	1993–2022 daily minimum and maximum air-temperature product	Temperature forcing
WGN	SWAT+ weather generator	2021–2022 precipitation infilling	WGN sensitivity

DGM, Direction Générale de la Météorologie de Madagascar; HRU, hydrological response unit; JAXA, Japan Aerospace Exploration Agency; NASA POWER, National Aeronautics and Space Administration Prediction Of Worldwide Energy Resources; RFE, Rainfall Estimates; SWAT+, Soil and Water Assessment Tool Plus; WGN, SWAT+ weather generator.

Definition of the BACI zones

The BACI design uses the fixed Mandena mining polygon as the impact zone and the selected basin-internal polygon as the reference zone [10,12]. The four spatial quantities are reported separately: complete mining polygon, complete reference polygon, weighted mining-HRU intersections and weighted reference-HRU intersections.

The selected reference zone covered 1,379.7 ha, compared with 1,381.9 ha for the mining polygon, corresponding to an area difference of 0.16%. The complete polygon areas must be distinguished from

the effective HRU-intersection supports of 1,103.9 and 1,341.5 ha. The reference remains a basin-internal spatial comparator rather than a perfect experimental replicate [12,13].

For each of the 216 mining-zone and 308 reference-zone HRU intersections, the intersection area was calculated. For each of the nine tested outputs and both forcing diagnostics, the annual zone value was computed as $\bar{X}_{z,y} = \sum_i (a_{i,z} X_{i,y}) / \sum_i a_{i,z}$, where $X_{i,y}$ is the annual SWAT+ value for HRU i in year y and $a_{i,z}$ is the area of that HRU intersecting zone z . Thus, “annual intersection-weighted values” are annual HRU outputs averaged with fixed HRU–zone overlap areas as weights. The circular reference boundary determines the included HRU fractions; it is not assumed to be geometrically equivalent to the mining polygon.

BACI computation

For each year y , the area-weighted mining-minus-reference difference was calculated from the annual weighted means of the mining zone (M_y) and reference zone (R_y). The descriptive double difference for each year from 2008 onward was then calculated as follows:

$$BACI_y = (M_y - M_{pre}) - (R_y - R_{pre}) \quad (1)$$

where M_{pre} and R_{pre} are the 1993–2007 means of the two zones [10–12]. This equation expresses each post-2008 annual contrast relative to the zone-specific pre-period means.

Formal inference used all 30 annual differences $D_y = M_y - R_y$. For each of the nine hydrological responses, the following model was fitted, with $Post_y$ equal to zero for 1993–2007 and one for 2008–2022:

$$D_y = \beta_0 + \beta_1 Post_y + \epsilon_y \quad (2)$$

The coefficient β_1 estimates the mean threshold-associated change in the mining-minus-reference difference. Heteroskedasticity- and autocorrelation-consistent (HAC) standard errors used the Newey–West estimator with a Bartlett kernel, a maximum lag of one year, the finite-sample covariance factor $n/(n - k)$, and Student-t inference with 28 degrees of freedom [33]. Two-sided p values were adjusted across the nine responses by Holm’s sequential procedure at $\alpha = 0.05$ [34]. Precipitation and potential evapotranspiration were treated as forcing diagnostics outside this family. The lag choice was checked for maximum lags of zero to three years.

Temporal-window check

A temporal-window check evaluated the influence of the two weather-generator-infilled precipitation years. Estimates for the complete post-period 2008–2022 ($n = 15$) were compared with estimates for 2008–2020 ($n = 13$). No analysis excluding 2011 was retained because the archived workflow contained no documented prior diagnostic that justified that exclusion.

The same BACI variables, weighting rules and pre-period means were used in both windows. This check evaluated the dependence on the final two years of the record; it does not change the SWAT+ inputs or outputs and is not an input-parameter temporal-window check.

For each window, annual means, standard deviations and sign counts were recalculated. The comparison is descriptive and shows whether interpretation depends on 2021–2022; it does not replace the formal 30-year regression.

Low-, intermediate- and high-magnitude parameter-perturbation scenarios

As a separate complement to the mining-versus-reference temporal comparison, three mining-zone scenarios were built from the baseline TxtInOut. “Low”, “intermediate” and “high” denote increasingly large, predefined changes to vegetation, surface and soil parameters; they do not represent measured, reconstructed or calibrated disturbance intensity. This scenario chain was excluded from the central temporal inference and was used only to quantify model response when those parameter changes are imposed.

The scenario selection comprises 158 HRUs already present in the archived scenario chain, including 144 non-wetland HRUs and 14 wetland HRUs. These 158 units are a scenario subset and are distinct from the 216 HRUs intersecting the mining polygon in the BACI aggregation.

The low-, intermediate- and high-magnitude scenarios were created by duplicating the baseline TxtInOut and reassigning the same 158 selected HRUs to scenario land-cover, soil and plant definitions. The modified terms were curve number, surface roughness, leaf area, biomass, residue cover and soil available water capacity [4–7,28,35]. Soil profiles were copied from the SoilGrids-based baseline profiles before the available-water-capacity multipliers were applied.

Relative to the baseline, the low-, intermediate- and high-magnitude scenarios applied overland-roughness factors of 0.90, 0.75 and 0.60; leaf-area and biomass factors of 0.70, 0.40 and 0.15; residue-cover factors of 0.80, 0.60 and 0.40; and soil available-water-capacity factors of 0.90, 0.75 and 0.60, respectively. Across hydrologic soil groups A–D, curve-number increments were 3/4/5/5, 6/8/9/9 and 9/11/12/12, with respective caps of 85/89/92/94, 88/92/94/95 and 90/94/95/96. Precipitation and temperature were identical between baseline and scenario runs, so differences arise from the imposed HRU-parameter changes.

For each scenario, annual values were aligned with the baseline by HRU identifier and year. The response was defined as $\Delta_y = S_y - B_y$, where S_y and B_y are the scenario and baseline outputs for the same HRU and year. Responses were summarised over 2008–2022 to align reporting with the operational period. These deltas quantify model sensitivity to the imposed changes and are not part of the mining-versus-reference temporal inference; the reporting window does not convert them into intervention estimates.

Quality controls and consistency checks of SWAT+ outputs

The baseline and the low-, intermediate- and high-magnitude execution folders, completion files and annual outputs were checked before interpretation. All four `hru_wb_yr` tables contain the same number of rows, and the archived SHA-256 fingerprints identify the frozen files.

Scenario audits verified the same 158 HRU identifiers in the low-, intermediate- and high-magnitude runs, separated into 144 non-wetland and 14 wetland units. The 474 reassignment records correspond to 158 HRUs in each of the three scenarios. HRU, land-cover, curve-number, soil and plant links were checked, and scenario–baseline comparisons were aligned by HRU and year.

$$Residual = P - ET - WYLD - PERC - \Delta SW \quad (3)$$

where P is precipitation, ET actual evapotranspiration, $WYLD$ simulated water yield, $PERC$ percolation and ΔSW annual change in storage. Residual summaries, units, year coverage and identifier matching were used as consistency checks rather than hydrometric validation. Some archived audit tables set pre-2008 display deltas to zero as a post-processing convention. Those display values were not used to infer equality between scenario and baseline runs before 2008.

Statistical analysis and interpretation

Inference is based on β_1 , its Newey–West standard error, the two-sided p value and the Holm-adjusted p value. The standard deviation and sign counts describe dispersion and direction, respectively. A response is not reported as detected when its Holm-adjusted p value exceeds 0.05.

Precipitation and PET were treated as diagnostic variables. Precipitation serves to verify the matching of rainfall forcing between the mining and reference zones. PET serves to verify the coherence of the hydrometeorological calculation, but is not interpreted as a mining response.

Scenario-minus-baseline deltas are reported separately from BACI estimates. They describe the response produced by SWAT+ under imposed parameter changes and do not test whether a mining effect occurred in the baseline trajectory.

Results

Climate-forcing diagnostics

Precipitation was used as a post-selection diagnostic of forcing comparability between the two spatial supports. Over 2008–2022, the mean precipitation BACI contrast was -4.56 mm yr^{-1} , with a median of zero, 13 years exactly equal to zero and two negative years. The negative mean arose only in 2021–2022, when precipitation was infilled by the SWAT+ weather generator.

After removal of 2021–2022, the mean precipitation BACI contrast was exactly zero. Over 1993–2020, the period covered by the DGM RFE product, the mining and reference aggregations therefore received the same precipitation forcing. The small imbalance in the full post-period is a weather-generator diagnostic, not a persistent spatial difference in the DGM RFE forcing.

Potential evapotranspiration behaved differently: its mean BACI contrast was + 1.61 mm yr⁻¹ over 2008–2022 and + 1.96 mm yr⁻¹ over 2008–2020. This contrast did not depend on the weather-generator rainfall infilling. It is retained only as a diagnostic of the Penman–Monteith calculation and is not interpreted as a mining response.

Threshold-associated shifts in annual zone differences

None of the nine hydrological responses showed a threshold-associated change after Holm correction (all adjusted $p = 1.000$; Table 2). The estimates were small relative to annual dispersion, and the inference was unchanged across the HAC maximum-lag checks. Annual double differences are shown in Fig. 2.

Percolation had the largest negative estimate ($\beta_1 = -5.46$ mm yr⁻¹, HAC SE = 5.99, $p = 0.370$). Its annual standard deviation was 21.52 mm, and the contrast was negative in 10 of 15 post-2008 years. The Holm-adjusted p value was 1.000.

Water yield ($\beta_1 = -2.56$ mm yr⁻¹, $p = 0.652$) and generated surface runoff ($\beta_1 = -2.22$ mm yr⁻¹, $p = 0.723$) likewise showed no threshold-associated divergence. Their Holm-adjusted p values were 1.000.

Mean soil water, final soil water and annual soil-water change were estimated to be - 1.49, + 1.38 and + 1.98 mm yr⁻¹, respectively. None approached the 0.05 threshold before or after multiplicity correction.

Actual evapotranspiration, plant transpiration and soil evaporation were estimated to be + 1.05, + 0.42 and + 1.47 mm yr⁻¹, respectively. Their raw p values ranged from 0.860 to 0.975, and all Holm-adjusted p values were 1.000.

Table 2
Threshold-associated BACI estimates and formal inference for nine hydrological responses

Response	β_1	HAC SE	Raw p	Holm p	Annual SD	Post signs
Percolation	-5.4583	5.9874	0.3697	1.000	21.52	10- / 5+
Water yield	-2.5615	5.6252	0.6524	1.000	16.32	8- / 7+
Generated runoff	-2.2188	6.1970	0.7230	1.000	18.25	8- / 7+
Mean soil water	-1.4928	2.4413	0.5458	1.000	6.91	8- / 7+
Final soil water	1.3825	2.7955	0.6248	1.000	7.28	7- / 8+
Soil-water change	1.9808	3.1857	0.5391	1.000	9.83	5- / 10+
Actual ET	1.0481	8.9736	0.9079	1.000	21.25	9- / 6+
Plant transpiration	0.4224	13.1477	0.9746	1.000	38.45	6- / 9+
Soil evaporation	1.4745	8.2639	0.8597	1.000	29.14	6- / 9+

β_1 is the post-2008 coefficient from the 30-year mining-minus-reference regression and estimates a threshold-associated change in the zone difference. HAC standard errors use Newey–West lag 1 with small-sample correction and Student-t inference. Holm adjustment controls the family-wise error rate across nine tests. SD is the standard deviation of the 15 annual post-2008 contrasts. Post signs give the numbers of negative and positive annual contrasts, respectively; for example, 10- / 5+ denotes 10 negative and five positive years.

Shared directions of change in both zones

Post-minus-pre means calculated separately for the mining and reference zones show same-direction changes for several water-balance components (Table 3). The BACI double difference retains only the residual difference between the two zonal changes.

Percolation increases in both zones after 2008: +47.81 mm yr⁻¹ in the mining zone and + 53.27 mm yr⁻¹ in the reference zone. The BACI contrast of - 5.46 mm yr⁻¹ therefore indicates a smaller increase in the mining zone, not an absolute decline in percolation in that zone.

Simulated water yield decreases in both zones: -15.27 mm yr⁻¹ in the mining zone and - 12.71 mm yr⁻¹ in the reference zone. Generated surface runoff also decreases in both zones, with values of - 15.38 mm yr⁻¹ in the mining zone and - 13.16 mm yr⁻¹ in the reference zone. The negative BACI contrasts of these two variables therefore reflect a slightly stronger decrease in the mining zone, but the difference between zones remains small.

Actual evapotranspiration decreased in both zones: -6.41 mm yr⁻¹ in the mining zone and - 7.46 mm yr⁻¹ in the reference zone. Plant transpiration also decreased, by - 5.77 and - 6.19 mm yr⁻¹, respectively.

Final storage decreased by $-12.66 \text{ mm yr}^{-1}$ in the mining zone and $-14.05 \text{ mm yr}^{-1}$ in the reference zone. The shared directions limit attribution of the residual annual differences to a zone-specific post-2008 process.

Table 3
Absolute annual means by BACI zone and period

Variable	Mine 1993–2007	Mine 2008–2022	Reference 1993–2007	Reference 2008–2022
P	1599.13	1612.81	1599.13	1617.36
PET	1546.67	1518.60	1557.32	1527.63
ET	1049.17	1042.76	1158.09	1150.63
Ecanopy	73.44	75.98	110.60	113.98
Eplant	617.79	612.02	917.49	911.30
Esoil	357.93	354.76	130.00	125.35
Surq gen	100.31	84.93	49.55	36.39
Water yield	101.39	86.12	53.88	41.18
Percolation	462.10	509.91	381.91	435.17
SW ave	188.52	196.17	169.29	178.43
SW final	122.86	110.20	93.98	79.93
SW change	4.67	-8.22	5.25	-9.62

P, PET, ET, Ecanopy, Eplant, Esoil, Surq gen, water yield, percolation and SW change are reported in mm yr^{-1} ; SW ave and SW final are reported in mm. P, precipitation; PET, potential evapotranspiration; ET, actual evapotranspiration; Ecanopy, canopy-interception evaporation; Eplant, plant transpiration; Esoil, soil and surface-water evaporation reported in the SWAT+ output; Surq gen, generated surface runoff; SW ave, mean soil water; SW final, final soil water; SW change, annual soil-water change. $ET = Eplant + Esoil + Ecanopy$.

Temporal-window check excluding the weather-generator years 2021–2022

The temporal-window check compared 2008–2022 with 2008–2020, excluding the two weather-generator-infilled years. No exclusion of 2011 was retained.

The percolation contrast decreased in absolute magnitude from $-5.46 \pm 21.52 \text{ mm yr}^{-1}$ over 2008–2022 to $-2.29 \pm 21.29 \text{ mm yr}^{-1}$ over 2008–2020. Water yield changed from -2.56 ± 16.32 to $+0.21 \pm 15.72 \text{ mm yr}^{-1}$, and generated surface runoff changed from -2.22 ± 18.25 to $+0.87 \pm 17.57 \text{ mm yr}^{-1}$.

The evapotranspiration responses remained small relative to annual dispersion. Actual evapotranspiration changed from $+ 1.05 \pm 21.25$ to $+ 0.70 \pm 22.87$ mm yr⁻¹; plant transpiration from $+ 0.42 \pm 38.45$ to $+ 6.75 \pm 37.07$ mm yr⁻¹; and soil evaporation from $+ 1.47 \pm 29.14$ to $- 3.62 \pm 27.58$ mm yr⁻¹.

These changes do not alter the formal result (Table 4). They show that several descriptive means depend on the weather-generator-infilled years and should not be treated as stable annual mining responses.

Table 4
Temporal-window check for 2008–2022 and after removing the weather-generator-infilled years 2021–2022

Variable	2008–2022	2008–2020	Mean change	Interpretation
Precipitation	-4.56 ± 12.47	0.00 ± 0.00	$+ 4.56$	WGN diagnostic
Percolation	-5.46 ± 21.52	-2.29 ± 21.29	$+ 3.17$	weaker
Water yield	-2.56 ± 16.32	$+ 0.21 \pm 15.72$	$+ 2.77$	near zero
Generated runoff	-2.22 ± 18.25	$+ 0.87 \pm 17.57$	$+ 3.09$	near zero
Actual ET	$+ 1.05 \pm 21.25$	$+ 0.70 \pm 22.87$	-0.34	small
Plant transpiration	$+ 0.42 \pm 38.45$	$+ 6.75 \pm 37.07$	$+ 6.33$	dispersed
Soil evaporation	$+ 1.47 \pm 29.14$	-3.62 ± 27.58	-5.10	sign change
Final soil water	$+ 1.38 \pm 7.28$	$+ 0.38 \pm 7.06$	-1.00	small
Soil-water change	$+ 1.98 \pm 9.83$	$+ 0.66 \pm 9.93$	-1.32	small

Values are annual mean $\pm$ SD (mm yr⁻¹); mean change is the reduced-window minus complete-window mean. ET, actual evapotranspiration; SD, standard deviation; WGN, SWAT+ weather generator. Sample sizes are 15 and 13 years, respectively.

Responses to low-, intermediate- and high-magnitude parameter perturbations

The low-, intermediate- and high-magnitude parameter-perturbation scenarios produced directional scenario-minus-baseline responses (Fig. 3; Table 5). Because these responses arise only after the parameters are imposed on selected HRUs, they are interpreted as model sensitivity, not as evidence that mining caused a corresponding change in the baseline trajectories.

All three parameter-perturbation scenarios completed successfully. Each changed the same 158 selected HRUs: 144 non-wetland and 14 wetland units. Precipitation and potential evapotranspiration were identical between baseline and scenario runs. The reported hydrological differences therefore arise from the specified vegetation, surface and soil parameter changes.

In the 144 non-wetland HRUs, the scenarios redistributed the simulated water balance. Plant transpiration decreased in all 15 post-2008 years, with means of -110.35 , -341.83 and -552.96 mm yr⁻¹ under the low-, intermediate- and high-magnitude scenarios, respectively. Soil evaporation increased by $+86.76$, $+185.15$ and $+359.01$ mm yr⁻¹, whereas actual evapotranspiration decreased by -29.79 , -170.56 and -225.17 mm yr⁻¹.

Outflow fluxes increased in the non-wetland HRUs. Generated surface runoff increased by $+20.31$, $+54.11$ and $+96.55$ mm yr⁻¹ under the low-, intermediate- and high-magnitude scenarios, respectively, and simulated water yield increased by $+20.31$, $+54.45$ and $+96.90$ mm yr⁻¹. Percolation responded non-linearly: $+9.12$, $+113.82$ and $+125.04$ mm yr⁻¹. Mean curve-number increases were $+4.98$, $+10.44$ and $+14.99$ points.

For the non-wetland HRUs, the imposed parameter changes redistribute simulated water among transpiration, soil evaporation, total evapotranspiration, generated surface runoff, water yield and percolation. Percolation did not increase proportionally across the low-, intermediate- and high-magnitude sequence: most of the increase occurs between the low- and intermediate-magnitude sets, followed by little additional change under the high-magnitude set. These results describe the response of SWAT+ water-balance processes to the specified inputs; they do not identify a historical mining effect.

Table 5
Scenario-minus-baseline responses of selected mining-zone HRUs over 2008–2022

HRU group	HRUs	n	Variable	Low	Intermediate	High
Non-wetland	144	15	eplant	-110.35 ± 26.00	-341.83 ± 59.54	-552.96 ± 63.64
Non-wetland	144	15	esoil	$+ 86.76 \pm 26.50$	$+ 185.15 \pm 46.08$	$+ 359.01 \pm 63.81$
Non-wetland	144	15	ET	-29.79 ± 20.63	-170.56 ± 47.92	-225.17 ± 50.58
Non-wetland	144	15	surq_gen	$+ 20.31 \pm 13.10$	$+ 54.11 \pm 32.59$	$+ 96.55 \pm 54.52$
Non-wetland	144	15	water yield	$+ 20.31 \pm 13.08$	$+ 54.45 \pm 32.56$	$+ 96.90 \pm 54.41$
Non-wetland	144	15	PERC	$+ 9.12 \pm 22.98$	$+ 113.82 \pm 47.19$	$+ 125.04 \pm 57.89$
Wetland	14	15	ET	$+ 145.05 \pm 40.39$	$+ 272.00 \pm 67.58$	$+ 380.30 \pm 92.80$
Wetland	14	15	esoil	$+ 150.75 \pm 42.20$	$+ 287.33 \pm 69.52$	$+ 411.25 \pm 97.51$
Wetland	14	15	water yield	-59.48 ± 17.28	-112.07 ± 25.66	-149.75 ± 34.45
Wetland	14	15	PERC	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00

Values are annual mean $\pm$ SD in mm yr⁻¹. The Low, Intermediate and High columns denote the low-, intermediate- and high-magnitude predefined parameter changes. Eplant, plant transpiration; Esoil, soil and surface-water evaporation reported in the SWAT+ output; ET, actual evapotranspiration; Surq gen, generated surface runoff; PERC, percolation; HRU, hydrological response unit; n, number of annual values; SD, standard deviation. Positive values indicate an increase relative to baseline and negative values a decrease. Non-wetland and wetland HRUs are reported separately.

Distinct response of the wetland HRUs

The 14 wetland HRUs responded differently from the non-wetland HRUs. Evapotranspiration increased by + 145.05, + 272.00 and + 380.30 mm yr⁻¹ under the low-, intermediate- and high-magnitude scenarios, respectively. Soil evaporation increased by + 150.75, + 287.33 and + 411.25 mm yr⁻¹. Conversely, generated surface runoff and simulated water yield decreased; water-yield differences were – 59.48, – 112.07 and – 149.75 mm yr⁻¹.

Percolation remained zero in the wetland HRUs under the low-, intermediate- and high-magnitude scenarios. Their simulated response was therefore characterised by increased evapotranspiration and

decreased water yield, supporting reporting these wetland HRUs separately from non-wetland terrestrial HRUs.

Synthesis of the results

The temporal inference and the scenario comparison answer different questions. The 30-year regressions detected no threshold-associated divergence for the nine hydrological responses after Holm correction, whereas imposed parameter changes produced substantial scenario-minus-baseline responses in selected HRUs.

The low-, intermediate- and high-magnitude parameter-perturbation scenarios show a marked redistribution in selected mining-zone HRUs. In non-wetland HRUs, plant transpiration decreases, soil evaporation increases, actual evapotranspiration decreases, and generated runoff, simulated water yield and percolation increase. Percolation changes little under the low-magnitude set, rises under the intermediate-magnitude set and then changes little further under the high-magnitude set. Wetland HRUs instead show increased evapotranspiration and decreased simulated water yield.

In summary, the baseline outputs did not show a statistically detected post-2008 level shift unique to the mining-zone difference. The separate parameter experiment showed that SWAT+ redistributed the simulated water balance when specified HRU parameters were changed. The findings answer different questions and cannot be combined as causal evidence.

Discussion

No detected threshold-associated annual divergence

The retrospective BACI-style analysis detected no threshold-associated divergence for any of the nine hydrological responses after Holm correction (all adjusted $p = 1.000$). This result does not demonstrate the absence of local mining effects. It means that annual area-weighted mining-minus-reference outputs from this SWAT+ configuration do not isolate a post-2008 level shift.

This bounded interpretation prevents over-attribution. Percolation increased in both zones, whereas simulated water yield, generated surface runoff and actual evapotranspiration decreased in both zones. The BACI coefficient retains only the difference between these shared directional changes; it is not an absolute change directly attributable to mining.

The β_1 estimates were small relative to annual dispersion, and the stated threshold hypothesis was not supported. Same-direction zonal changes are compatible with common forcing or shared model structure, but the present analysis does not partition those explanations.

The temporal result cannot determine whether mining disturbance was insufficient to alter soil properties. Soil properties were not observed before and after operations, and the baseline SWAT+ configuration does not contain a measured year-by-year history of disturbance. The low-, intermediate-

and high-magnitude scenario experiment demonstrates sensitivity to specified soil and vegetation parameters but cannot establish whether, when or to what degree those changes occurred in Mandena.

Why percolation should not be over-interpreted

Percolation had the most negative estimate, but it was not statistically detected ($\beta_1 = -5.46 \text{ mm yr}^{-1}$, $p = 0.370$; Holm $p = 1.000$). Percolation increased from 462.10 to 509.91 mm yr^{-1} in the mining zone and from 381.91 to 435.17 mm yr^{-1} in the reference zone. The negative coefficient therefore represents a smaller increase in mining-zone outputs, not an absolute decline.

The temporal-window check reduced the mean contrast to -2.29 mm yr^{-1} after 2021–2022 were removed. Percolation can therefore be reported as the largest negative estimate, but not as an isolated annual mining response.

Formal inference rests on the HAC standard error and Holm-adjusted p value, while annual dispersion and sign counts are retained as descriptive information.

Interpretation of simulated water yield and runoff

Simulated water yield and generated surface runoff had negative mean BACI contrasts over 2008–2022, but both became close to zero when 2021–2022 were removed. Their descriptive means therefore depend on the temporal window.

Both outputs decreased after 2008 in the mining and reference zones. The negative coefficient indicates only a slightly larger decrease in mining-zone outputs, and the zone difference was small relative to annual variation.

The annual temporal comparison therefore provides no statistically detected separation of mining-zone and reference-zone water-yield or runoff outputs. Monthly, seasonal or event-scale observations would be required to assess shorter responses [7,28].

Forcing diagnostics delimit interpretation

The precipitation BACI contrast was zero over 1993–2020, the period covered by the DGM RFE product [26,27]. The small full-period residual arose from weather-generator infilling in 2021–2022. This demonstrates equal DGM RFE precipitation forcing for the two aggregations over 1993–2020, but it does not establish equivalence in soils, vegetation, drainage or basin position.

Removing 2021–2022 reduced several descriptive contrasts but did not change the formal finding. The overall result is therefore less dependent on the endpoint window than some individual means suggest, while the weather-generator years remain unsuitable for assessing a spatial rainfall difference.

The potential-evapotranspiration contrast remained small and positive after those years were removed. It is retained as a Penman–Monteith diagnostic [25], not as an indicator of mining response. In the

scenario chain, climate forcing was identical among runs, so scenario differences arose from imposed HRU-parameter changes.

Parameter-perturbation sensitivity is distinct from the annual temporal comparison

The low-, intermediate- and high-magnitude parameter-perturbation scenarios answer a different question from the mining-zone-versus-reference temporal comparison. They impose predefined changes of increasing magnitude to vegetation, surface and soil parameters in selected mining-zone HRUs and measure scenario-minus-baseline outputs. They do not compare the mining zone with the reference zone and do not test the post-2008 hypothesis.

In non-wetland HRUs, SWAT+ simulated lower plant transpiration, higher soil evaporation, lower actual evapotranspiration, and higher generated surface runoff and water yield under the low-, intermediate- and high-magnitude parameter sets. Percolation changed little under the low-magnitude set, increased under the intermediate-magnitude set and changed little further under the high-magnitude set. This pattern is consistent with the model's representation of reduced vegetation parameter values and redistribution toward surface and drainage fluxes [4–7].

These scenario-minus-baseline differences establish that the simulated water-balance processes respond when the selected HRU parameters are changed. They do not establish that the same parameter changes occurred historically or that mining produced the baseline annual trajectories. The lack of a detected temporal contrast and the presence of scenario sensitivity are therefore compatible.

The distinction is between model sensitivity and temporal detection. The scenarios quantify what SWAT+ simulates under three specified parameter sets; the annual mining-zone-versus-reference analysis evaluates whether the baseline outputs contain a post-2008 relative level shift. Effects may be averaged, offset, shared or absent at the annual zonal scale, but the present design cannot distinguish among those explanations.

Role of the wetland HRUs

The wetland HRUs respond differently from the non-wetland HRUs in the scenario chain. Their evapotranspiration increases strongly, whereas their simulated water yield and generated surface runoff decrease. Percolation remains null. This inverse response justifies their separate treatment in the mining budgets.

Mixing the wetland and non-wetland HRUs would have blurred the interpretation. The non-wetland HRUs reflect a logic of cover reduction and redistribution towards runoff, simulated water yield and percolation. The wetland HRUs instead reflect a response dominated by evapotranspiration and by a different storage or saturation behaviour. Separating the two groups is therefore necessary to avoid an artificial mean mixing two opposite hydrological behaviours.

This separation is relevant in Mandena, where wetlands, open water and sandy soils coexist at low relief [1–3,17]. The fixed analytical mining polygon contains hydrologically different model units. Their scenario responses depend on whether an HRU is represented as wetland or non-wetland; they should therefore not be pooled into a single scenario mean.

Implications for environmental attribution

Same-direction changes in both zones do not identify their cause. They are compatible with common climate forcing, shared model configuration and spatial aggregation, but this study does not estimate the contribution of each explanation.

The separate low-, intermediate- and high-magnitude scenarios show how SWAT+ responds when selected vegetation, surface and soil parameters are changed. They do not show that equivalent parameter changes occurred historically, nor do they convert the retrospective threshold comparison into a causal mine-impact estimate.

The strongest supported inference is therefore limited: the annual baseline outputs contain no detected post-2008 mining-zone-minus-reference level shift, while imposed parameter changes redistribute the simulated water balance. Additional observations are needed to determine whether local changes occurred and what caused them.

Scope and limitations of the BACI design

The retrospective BACI-style design reduces variation shared by the two zones, but it does not remove all uncertainty [10,12,13]. The reference is a basin-internal comparator, not an experimental replicate. Differences in soils, microtopography, initial vegetation, local drainage or basin position may remain [12,35].

The second limitation concerns the temporal scale. The annual step can mask seasonal, monthly or event-scale responses [11,13]. Cover disturbance may affect the fluxes during certain periods of the year without strongly modifying the annual budgets. Similarly, changes in the response to heavy rainfall may be compensated by drier periods in the annual balance.

A further limitation concerns climate forcing. DGM RFE rainfall covers 1993–2020, whereas precipitation for 2021–2022 is produced by the SWAT+ weather generator. Removing those two years changes several descriptive contrasts but not the formal finding.

This study did not estimate a minimum disturbed area required for BACI detection. Detectability depends jointly on the disturbed area, reference support, annual variability, number of pre- and post-intervention years, and response magnitude [11–13]. A smaller affected fraction would generally contribute less to an area-weighted annual mean, but no numerical threshold can be inferred from the present single configuration. Estimating one would require a planned gradient of disturbed areas and repeated reference configurations.

A final limitation is the absence of continuous local streamflow calibration and of observed time-varying soil and land-disturbance data. Contrasts internal to one model configuration can reduce the influence of some absolute biases, but they do not replace hydrometric validation or document historical parameter change [31]. Results are therefore interpreted as simulated contrasts rather than measurements of real fluxes or direct estimates of mine impact.

Contribution to environmental modelling and monitoring

The study distinguishes three quantities that can otherwise be conflated: temporal change shared by both zones, a threshold-associated change in their difference, and model response to imposed parameters. The three quantities do not support the same inference.

Several annual outputs changed in the same direction in both zones, no hydrological β_1 estimate was detected after Holm correction, and the low-, intermediate- and high-magnitude scenarios produced sizeable responses in selected HRUs. This combination demonstrates model sensitivity without claiming historical occurrence or causal attribution.

For environmental assessment in mining settings, the result shows why a before–after analysis restricted to one zone can conflate shared and local change [10,12,13], while an imposed scenario alone can overstate historical detectability. Joint reporting of temporal contrasts and scenario sensitivity preserves their different evidential roles.

Implications for hydrological monitoring

Annual model outputs alone cannot resolve a local mining effect in this application. Future monitoring should combine monthly or seasonal diagnostics with local rainfall, measured water-table depth from piezometers, discharge observations where available, and separate wetland observations. Because no piezometric series was analysed, this study makes no inference about water-table depth or its temporal movement.

A basin-internal reference should be retained in future analyses, but additional reference configurations and sensitivity to spatial support should also be evaluated. Interpretation centred solely on the mining zone would risk assigning shared changes to a local source.

Wetland and non-wetland HRUs should be assessed separately. Their opposing simulated responses support monitoring designs that distinguish terrestrial drainage surfaces, wetlands and open water, with water-table status determined from observations rather than inferred from relief or model class.

Conclusion

The retrospective BACI-style analysis detected no threshold-associated divergence among the nine annual hydrological outputs after Holm correction. Several outputs changed in the same direction in the

mining and reference zones. These findings do not demonstrate the absence of local, seasonal or event-scale effects.

In parallel, the low-, intermediate- and high-magnitude scenarios produced a marked redistribution of the simulated water balance. In non-wetland HRUs, plant transpiration and actual evapotranspiration decreased, whereas soil evaporation, generated runoff, water yield and percolation increased under the imposed changes.

The supported conclusion is limited to two findings: no post-2008 level shift was detected in annual baseline mining-zone-minus-reference outputs, and SWAT+ redistributed the water balance when three specified magnitudes of HRU-parameter change were imposed. The scenario responses are not evidence of a historical mining effect. Stronger attribution requires observed discharge and piezometry, analysis at finer temporal resolution, time-varying disturbance data and additional reference configurations.

Declarations

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Author contributions

Z.R.R. conceived and designed the study, assembled and processed the spatial and climate data, configured and ran the SWAT+ simulations and scenario chain, performed the BACI and temporal-window checks, prepared the figures and tables, and wrote the manuscript. As the sole author, Z.R.R. is responsible for all aspects of the work.

Competing interests

The author declares that there are no competing interests.

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Ethics approval and consent to participate

Not applicable. The study did not involve human participants, human data, animals or biological materials.

Clinical trial number: not applicable.

Data availability

The datasets generated and analysed during the current study, including the SWAT+ TxtInOut inputs, the annual and monthly HRU water-balance outputs, the BACI tables, the temporal-window-check files, the scenario-chain summaries and the figure source data, are openly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.21633869>. Third-party input datasets are available from their original providers: ESA WorldCover 2021 (<https://doi.org/10.5281/zenodo.7254221>), AW3D30 (JAXA), SoilGrids 2.0 (Poggio et al.), the DGM Maproom / Madagascar Climate Data Library Rainfall Estimates product, and NASA POWER.

Code availability

The custom scripts used to construct the BACI design, compute annual contrasts, assemble the low-, intermediate- and high-magnitude scenario summaries, generate tables and render figures are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.21633869>. The repository also contains two reproducibility packages. The package `mandena_10_additional_hac_holm_statistics.zip` contains the authenticated `baci_results.xlsx` input, HAC and Holm scripts, requirements, tests, manifests and results. The package `mandena_11_figure1_full_reproduction.zip` contains the authenticated spatial inputs, Natural Earth 5.1.1, an offline Windows wheelhouse, the generation script, manifests and reference outputs. These packages do not rerun SWAT+ or alter the archived SWAT+ inputs and outputs.

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References

1. Acreman, M. & Holden, J. How Wetlands Affect Floods. *Wetlands* **33**, 773–786 (2013). <https://doi.org/10.1007/s13157-013-0473-2>
2. Bullock, A. & Acreman, M. The role of wetlands in the hydrological cycle. *Hydrol. Earth Syst. Sci.* **7**, 358–389 (2003). <https://doi.org/10.5194/hess-7-358-2003>
3. Mitsch, W. J. *Wetlands*. (John Wiley & Sons, Incorporated, Newark, 2015).
4. Bosch, J. M. & Hewlett, J. D. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**, 3–23 (1982). [https://doi.org/10.1016/0022-1694\(82\)90117-2](https://doi.org/10.1016/0022-1694(82)90117-2)
5. Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W. & Vertessy, R. A. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**, 28–61 (2005). <https://doi.org/10.1016/j.jhydrol.2004.12.010>
6. Bruijnzeel, L. A. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment* **104**, 185–228 (2004). <https://doi.org/10.1016/j.agee.2004.01.015>

7. DeFries, R. & Eshleman, K. N. Land-use change and hydrologic processes: a major focus for the future. *Hydrological Processes* **18**, 2183–2186 (2004). <https://doi.org/10.1002/hyp.5584>
8. Bisht, A. & Martinez-Alier, J. Coastal sand mining of heavy mineral sands: Contestations, resistance, and ecological distribution conflicts at HMS extraction frontiers across the world. *J of Industrial Ecology* **27**, 238–253 (2023). <https://doi.org/10.1111/jiec.13358>
9. Van Gosen, B. S., Fey, D. L., Shah, A. K., Verplanck, P. L. & Hoefen, T. M. Deposit Model for Heavy-Mineral Sands in Coastal Environments. 51 p. (2014). <https://doi.org/10.3133/sir20105070L>
10. Stewart-Oaten, A., Murdoch, W. W. & Parker, K. R. Environmental Impact Assessment: 'Pseudoreplication' in Time? *Ecology* **67**, 929–940 (1986). <https://doi.org/10.2307/1939815>
11. Underwood, A. J. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology* **161**, 145–178 (1992). [https://doi.org/10.1016/0022-0981\(92\)90094-Q](https://doi.org/10.1016/0022-0981(92)90094-Q)
12. Underwood, A. J. On Beyond BACI: Sampling Designs that Might Reliably Detect Environmental Disturbances. *Ecological Applications* **4**, 3–15 (1994). <https://doi.org/10.2307/1942110>
13. Benedetti-Cecchi, L. Beyond BACI: optimization of environmental sampling designs through monitoring and simulation. *Ecological Applications* **11**, 783–799 (2001). [https://doi.org/10.1890/1051-0761\(2001\)011\[0783:BBOOES\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011[0783:BBOOES]2.0.CO;2)
14. Green, R. H. *Sampling Design and Statistical Methods for Environmental Biologists*. (Wiley, New York, NY, 1979).
15. Bollen, A. & Donati, G. Conservation status of the littoral forest of south-eastern Madagascar: a review. *Oryx* **40**, 57–66 (2006). <https://doi.org/10.1017/S0030605306000111>
16. Consiglio, T. et al. Deforestation and Plant Diversity of Madagascar's Littoral Forests. *Conservation Biology* **20**, 1799–1803 (2006). <https://doi.org/10.1111/j.1523-1739.2006.00562.x>
17. Vincelette, M., Dumouchel, J., Giroux, J. & Heriarivo, R. The Tolagnaro (Fort Dauphin) Region: A Brief Overview of the Geology, Hydrology and Climatology. in *Biodiversity, Ecology and Conservation of Littoral Ecosystems in Southeastern Madagascar, Tolagnaro (Fort Dauphin)* (eds Ganzhorn, J. U., Goodman, S. M. & Vincelette, M.) 9–17 (Smithsonian Institution, Washington, DC, 2007).
18. Virah-Sawmy, M., Willis, K. J. & Gillson, L. Threshold response of Madagascar's littoral forest to sea-level rise. *Global Ecology and Biogeography* **18**, 98–110 (2009). <https://doi.org/10.1111/j.1466-8238.2008.00429.x>
19. Institute of Developing Economies, Japan External Trade Organization. Rio Tinto: AGE African Growing Enterprises File. https://www.ide.go.jp/English/Data/Africa_file/Company/madagascar01.html (accessed 31 August 2026).
20. Rio Tinto. QIT Madagascar Minerals. <https://www.riotinto.com/en/operations/africa/qit-madagascar-minerals> (accessed 31 August 2026).
21. Yager, T. R. *The Mineral Industry of Madagascar in 2008*. <https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/country/2008/myb3-2008-ma.pdf>

- (2010).
22. Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. Large-area hydrologic modeling and assessment. Part I: model development. *Journal of the American Water Resources Association* 34, 73–89 (1998). <https://doi.org/10.1111/j.1752-1688.1998.tb05961.x>
 23. Bieger, K. et al. Introduction to SWAT+, a completely restructured version of the Soil and Water Assessment Tool. *Journal of the American Water Resources Association* 53, 115–130 (2017). <https://doi.org/10.1111/1752-1688.12482>
 24. Gassman, P. W., Reyes, M. R., Green, C. H. & Arnold, J. G. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE* 50, 1211–1250 (2007). <https://doi.org/10.13031/2013.23637>
 25. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. (Food and Agriculture Organization of the United Nations, Rome, 1998).
 26. Direction Générale de la Météorologie de Madagascar. Meteo Malagasy Maproom. <https://map.meteomadagascar.mg/maproom/index.html> (accessed 31 August 2026).
 27. Randriamarolaza, L. Y. A., Aguilar, E., Skrynyk, O., Vicente-Serrano, S. M. & Domínguez-Castro, F. Indices for daily temperature and precipitation in Madagascar, based on quality-controlled and homogenized data, 1950–2018. *Intl Journal of Climatology* 42, 265–288 (2022). <https://doi.org/10.1002/joc.7243>
 28. SWAT+ Development Team. SWAT+ Theoretical Documentation: Runoff Volume, SCS Curve Number Procedure. <https://swatplus.gitbook.io/io-docs/theoretical-documentation/section-2-hydrology/chapter-2-1-surface-runoff/2-1.1-runoff-volume-scs-curve-number-procedure> (accessed 31 August 2026).
 29. Japan Aerospace Exploration Agency. ALOS Global Digital Surface Model 'ALOS World 3D - 30m (AW3D30)'. https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm (accessed 31 August 2026).
 30. Zanaga, D. et al. ESA WorldCover 10 m 2021 v200. Zenodo (2022). <https://doi.org/10.5281/zenodo.7254221>
 31. Arnold, J. G. et al. SWAT: Model Use, Calibration, and Validation. *Transactions of the ASABE* 55, 1491–1508 (2012). <https://doi.org/10.13031/2013.42256>
 32. National Aeronautics and Space Administration. Prediction Of Worldwide Energy Resources (POWER) Data Access Viewer. <https://power.larc.nasa.gov/data-access-viewer/> (accessed 31 August 2026).
 33. Newey, W. K. & West, K. D. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica* 55, 703–708 (1987). <https://doi.org/10.2307/1913610>
 34. Holm, S. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics* 6, 65–70 (1979). <https://doi.org/10.2307/4615733>
 35. Poggio, L. et al. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *SOIL* 7, 217–240 (2021). <https://doi.org/10.5194/soil-7-217-2021>

Figures

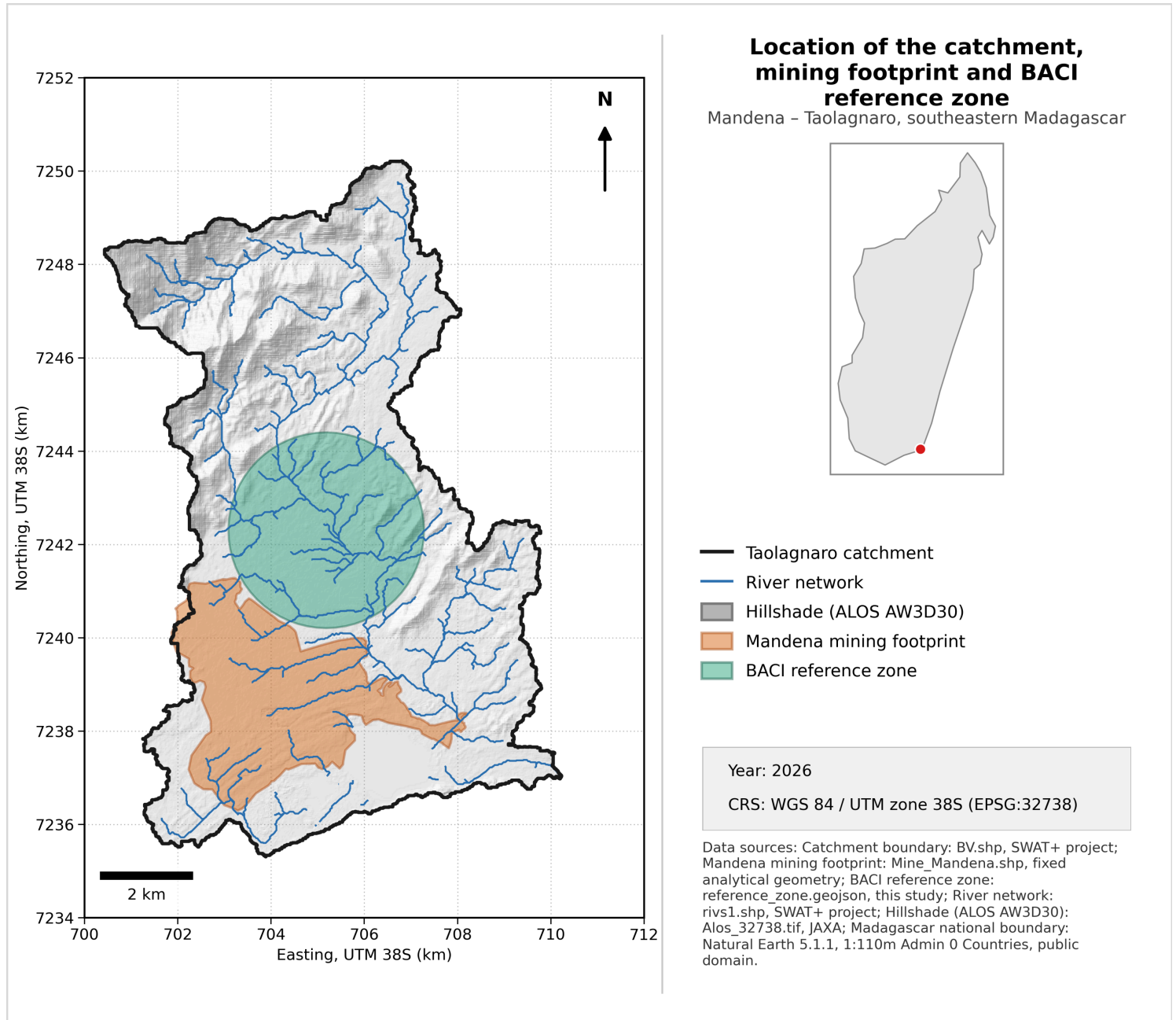


Figure 1

Location of the basin, fixed mining polygon and BACI reference zone. The map shows the basin boundary, SWAT+ stream network, Mine_Mandena.shp analytical polygon and basin-internal reference. The topographic background is an AW3D30 hillshade in WGS 84 / UTM zone 38S (EPSG:32738). The inset uses the Madagascar national boundary from Natural Earth 5.1.1, 1:110m Admin 0 Countries (<https://www.naturalearthdata.com>), public domain. The author generated the map in Python 3.12.13 with Matplotlib 3.10.8. The reproduction package for Fig. 1 provides the layer inventory, versions and checksums. BACI, before–after–control–impact; HRU, hydrological response unit

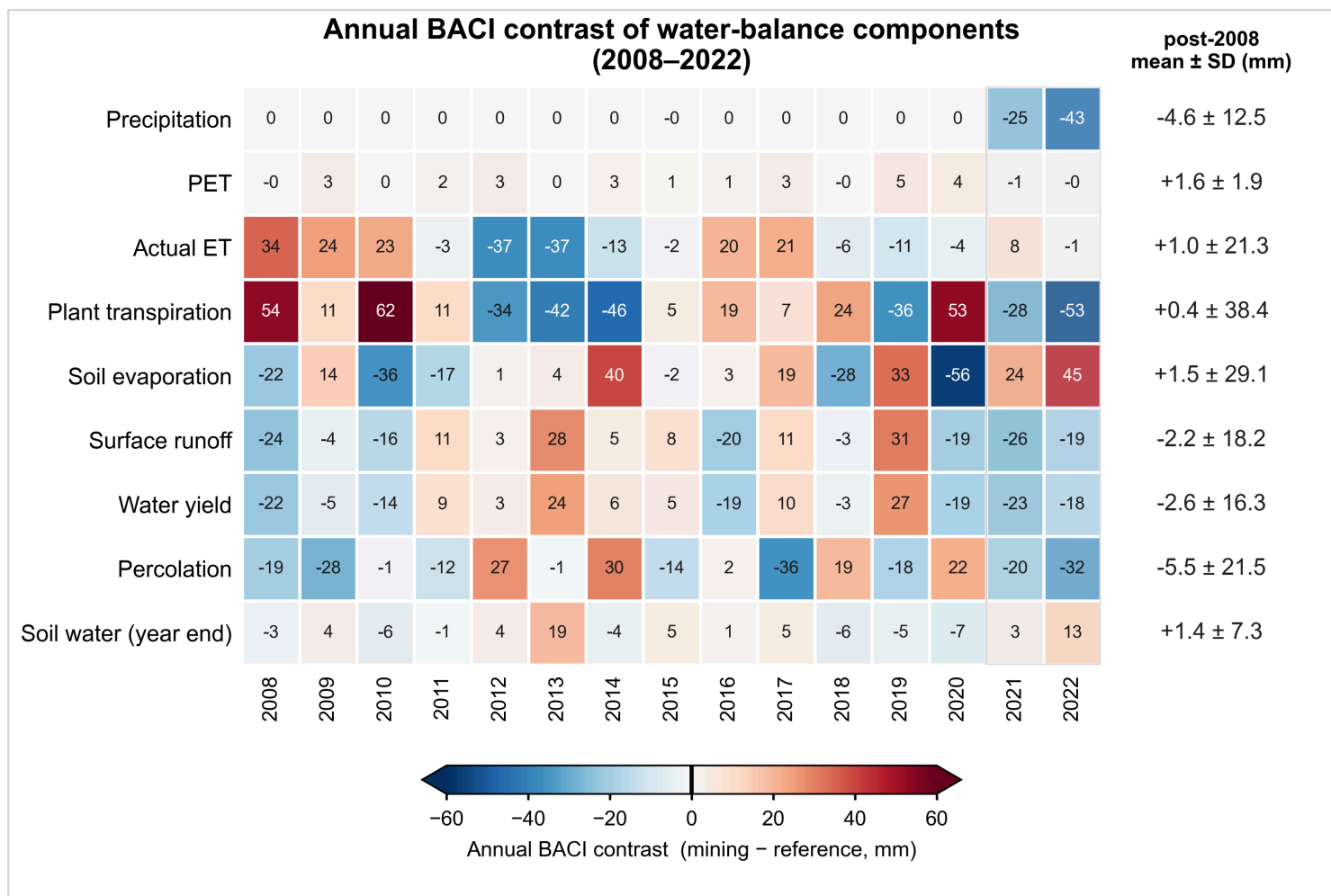


Figure 2

Annual post-2008 BACI contrasts for the main water-balance components. Rows correspond to hydrological variables, columns to years, and colours represent the BACI double difference (mm) after removal of each zone's pre-2008 mean. Values on the right are post-2008 means $\pm$ standard deviations. The 2021–2022 columns are flagged because precipitation in those years was infilled by the SWAT+ weather generator. BACI, before–after–control–impact; ET, actual evapotranspiration; surq_gen, generated surface runoff; sw_final, final soil-water storage; eplant, plant transpiration; esoil, soil evaporation

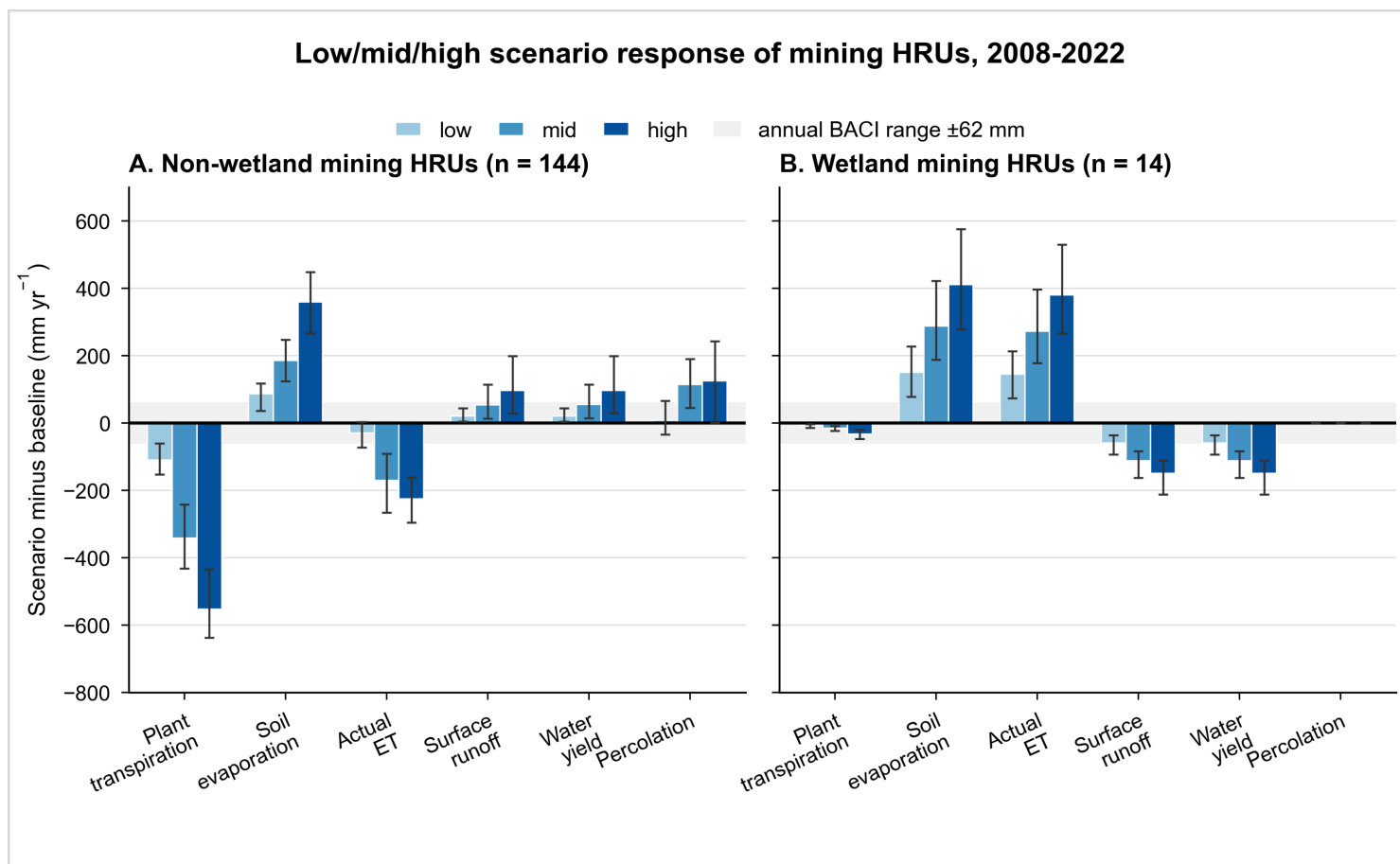


Figure 3

Imposed hydrological response of selected mining-zone HRUs under the low-, intermediate- and high-magnitude scenarios, expressed as the annual scenario-minus-baseline difference over 2008–2022. Panel (a) shows 144 non-wetland HRUs and panel (b) 14 wetland HRUs. Bars are annual means and whiskers are interannual minimum–maximum ranges. The grey band shows the range of annual BACI contrasts in Fig. 2 for scale comparison only. HRU, hydrological response unit; BACI, before–after–control–impact