

# From Pit to Lake: UAV-Assisted Tracking of Hydrological and Geomorphological Transformation in the Stanisław-Południe Clay Mine, SW Poland

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## Abstract

The progressive flooding of the former Stanisław-Południe open-pit clay mine in Lower Silesia, SW Poland, provides a unique opportunity to document the hydrological and geomorphological evolution of a mid-scale post-mining excavation undergoing natural refilling. Annual monitoring from 2022 to 2025 integrated direct discharge measurements, in-situ physicochemical profiling, and high-resolution UAV-based photogrammetry (DJI M3M, 0.02 m GSD). Water levels rose from 171.98 m a.s.l. in 2022 to 177.23 m a.s.l. in 2025, a cumulative rise of 5.25 m. Annual inflow rate accelerated from  $\approx 1$  m/a to over 2.1 m/a after 2023. Eight active inflow points delivered 2.34 L/s in 2025. Internal slope reshaping was ongoing but confined to areas destined for submersion, with no destabilisation of the external pit rim detected.

**Keywords:** Post-mining lake, pit lake formation, UAV photogrammetry, water balance, slope stability, Lower Silesia

## Introduction

The transition of exhausted open-pit mines into pit lakes constitutes an increasingly recognised pathway for post-mining land reclamation across Central Europe (Major *et al.* 2025; McCullough *et al.* 2020). As surface dewatering ceases, former excavations refill naturally through groundwater recovery, direct precipitation, and surface runoff. The resulting water bodies may serve ecological, recreational, or water-retention functions. Yet, their formation is accompanied by significant geomorphological adjustments, including slope erosion and mass movements, which require careful long-term monitoring (Castendyk and Eary 2009).

The Stanisław-Południe site, operated by JAROS.A. in the Jaroszów area of the Świdnica County (Lower Silesia, SW Poland), was an open-pit clay mine extracting refractory clays and sub-coal Oligocene-Miocene-Pliocene clays until the cessation of mining operations. The excavation, located approximately 8 km east of Strzegom and 60 km west of Wrocław, covers approximately 54.7 ha with a total void volume of ca.  $9.79 \times 10^6$  m<sup>3</sup> above the

2022 reference water level of 171.98 m a.s.l. The geological setting comprises Oligocene-Miocene-Pliocene sequences of silts and clays, with two lignite seams, overlying Precambrian metamorphic schists, capped by Quaternary fluvio-glacial sands and gravels that constitute the primary aquifer supplying the forming lake (Trentowski 2021).

Previous water-balance modelling (Worsa-Kozak *et al.* 2023) forecast complete flooding within 30 to 130 years depending on precipitation scenario, with a maximum expected water level of ca. 200-201 m a.s.l., constrained by the hydraulic head of the surrounding Quaternary aquifer. The observed filling rate, however, had not yet been validated against real multi-year data. This paper presents the first four years of integrated monitoring (2022-2025), regarding outer-slope stability, water-chemistry classification, the water-balance model, pit-lake morphology, and the georeferencing approach, and demonstrates the replicability of the UAV-geomatics methodology for post-mining environmental assessment.

## Study Area and Geological Setting

The Stanisław-Południe excavation is situated in the southern part of the Strzegom Hills mesoregion within the Sudeten Foreland macroregion. The terrain shows a gentle northward slope from ca. 210 m a.s.l. to ca. 190 m a.s.l. beyond the pit rim. Land use in the surrounding area is predominantly agricultural, with the village of Rusko located to the north-east. The site drains into the Dąbia stream, a tributary of the Strzegomka River, within the Odra River catchment.

The stratigraphy of the deposit (Trentowski 2021; Cwojdzński *et al.* 2017) includes: (i) a Quaternary overburden of fluvioglacial sands and gravels (aquifer) underlain by till, (ii) Oligocene-Miocene-Pliocene silty-sandy deposits transitioning into refractory clays with two lignite seams, and (iii) a Precambrian schist and phyllite basement. The hydraulically most significant unit is the Quaternary sand-gravel aquifer in the southern sector, which is in direct hydraulic connection with the forming pit lake through a ca. 10 m thick saturated zone at elevations of ca. 195-205 m a.s.l. (Herbowy and Mađrala 2021). This southern aquifer is the dominant source of groundwater inflow and controls the eventual equilibrium water level. The pit floor lies at approximately 165-167 m a.s.l.

The climate of the Jarosów area is oceanic-continental with mountain influence from the adjacent Sudeten Range. Mean annual precipitation at the nearby Dobrogoszcz station (1956-2022 series) is 595.5 mm/a, with annual extremes of 419.8 mm/a (1969) and 909.9 mm/a (1977). Mean annual air temperature for 1990-2014 was 9.2 °C (Klein Tank 2002). These values informed the water-balance model developed in the 2023 forecast report (Worsa-Kozak *et al.* 2023)

## Methods

### Monitoring Design

Annual monitoring campaigns were conducted in the autumn of each year from 2022 to 2025, in compliance with the statutory monitoring framework. Each campaign combined hydrological and hydrogeological mapping with UAV-based terrain surveying. Two additional campaigns were performed

in spring (May 2022) and autumn (October 2022) during the baseline year.

### Hydrological and Hydrogeological Mapping

Surface inflow points above the water-table surface were identified by systematic traversal of accessible pit faces. At each active seepage point, discharge was measured three times using the volumetric bucket method (volume 0.2-4.2 L collected per measurement; time 1.4-40 s), and the mean value  $\bar{Q}$  was recorded. Basic physicochemical parameters – water temperature (T), pH, electrical conductivity (specific electrical conductance, PEW in  $\mu\text{S}/\text{cm}$ ), redox potential ( $E^h$ , mV), dissolved oxygen (mg/L), and chloride concentration (mg/L) – were measured in situ with a portable multi-parameter probe. All measurement locations were recorded on a georeferenced mine survey plan. Water-level elevation was determined by GNSS measurement at the shoreline.

### UAV-Based Photogrammetric Surveying

Terrain data were acquired using multirotor UAV platforms: DJI Phantom 4 Pro (2022–2023 campaigns, flight altitude 70 m, ground sampling distance  $\approx 2\text{--}3$  cm) and DJI M3M (2024–2025 campaigns, flight altitude 70 m, ground sampling distance  $\approx 2\text{--}3$  cm, resulting in a post-filtering point cloud of ca. 119 million points). Eight photogrammetric ground control points (GCPs) were surveyed per campaign using RTK-GNSS in the ETRS89/Poland CS2000 Zone 6 coordinate reference system, yielding horizontal geolocation accuracy of  $\pm 2\text{--}3$  cm and vertical accuracy of  $\pm 3\text{--}5$  cm in EVRF2007 datum. Point clouds were processed in Agisoft Metashape and exported as Digital Terrain Models (DTMs) at 0.2 m resolution after ground-point filtering.

The georeferencing process used permanent benchmark markers installed within the mining area, measured at the start of the monitoring programme and re-occupied at each subsequent campaign. RTK measurements were obtained with base corrections from the nearest ASG-EUPOS CORS station. This approach ensures inter-annual comparability.



*Volumetric and Change-Detection Analysis*

DTM-derived hypsometric curves were computed in QGIS by intersecting the DTM with horizontal planes at 1 m intervals. Inundated volumes were calculated as the void space between the DTM and each plane. Inter-annual surface deformation was quantified using a Cloud-to-Mesh (C2M) signed-distance analysis in CloudCompare, yielding vertically oriented displacement maps. Change zones were classified by genesis as natural (slope wash, instability, and erosion) or anthropogenic (surface grading). Uncertainty was highest near the water surface due to waterlogged conditions, which reduced GCP availability; these levels are flagged accordingly in the volumetric output.

*Water Balance Model*

A water balance model (Worsa-Kozak *et al.* 2023) was applied with the equation  $P + D = H + S \pm \Delta R$ , where P is atmospheric precipitation, D is groundwater inflow, H is surface outflow (zero during the filling phase), S is actual evapotranspiration estimated by the Pardé nomogram, and  $\Delta R$  is the change in storage. Three precipitation scenarios were adopted: maximum ( $P = 910$  mm/a), neutral ( $P = 604$  mm/a), and minimum ( $P = 420$  mm/a). The model was constrained by field-measured inflow rates and the known excavation hypsometry. The present paper compares observed water-level rises with model predictions as a four-year validation dataset.

**Results**

*Water Level and Filling Rate*

Water levels recorded at each autumn campaign demonstrate a consistent and

accelerating rise (Tab. 1). From October 2022 to September 2023 ( $\approx 11$  months), the surface rose by 0.97 m, equivalent to  $\approx 0.3$  cm/d. Between September 2023 and October 2024 ( $\approx 13$  months), the rise was 2.11 m ( $\approx 0.53$  cm/d). Between October 2024 and October 2025 ( $\approx 12$  months), the rise was a further 2.17 m ( $\approx 0.59$  cm/d). The cumulative rise over the entire monitoring period is 5.25 m, from 171.98 m a.s.l. to 177.23 m a.s.l. The acceleration beyond 2023 corresponds qualitatively to the increasing water-surface area intercepting precipitation and the growing volume of subaqueous inflow as formerly exposed seepage faces became submerged.

*Inflow Characteristics and Water Chemistry*

The number and spatial distribution of measurable inflow points above the water surface varied between campaigns, reflecting seasonal precipitation conditions and the progressive submersion of lower-elevation seepage faces. In May 2022, seven measurement points yielded a total of 4.04 L/s, dominated by a single high-discharge point (P2, 3.00 L/s) in the southern sector. By October 2022, total inflow had decreased to 1.54 L/s (eleven points), consistent with lower autumn precipitation following a dry winter. September 2023 recorded the highest measured total inflow at 6.93 L/s (eight points), with two major contributors (P3: 2.53 L/s; P8: 3.15 L/s) associated with concentrated drainage from the Quaternary sand-gravel aquifer outcropping in the southern wall. October 2024 and October 2025 returned lower totals of 1.92 L/s and 2.34 L/s, respectively, both reflecting drier autumn conditions.

**Table 1** Water level and inflow summary for the Stanisław-Południe monitoring campaigns, 2022–2025.

Campaign date	Water level (m a.s.l.)	Rise since the previous (m)	Measured inflow (L/s)	Annualised inflow (m <sup>3</sup> /a)
May 2022	–	–	4.044	127 540
Oct 2022	171.98	baseline	1.535	48 407
Sep 2023	172.95	0.97	6.932	218 612
Oct 2024	175.06	2.11	1.915	60 383
Oct 2025	177.23	2.17	2.340	73 819



The inflow waters are consistently slightly alkaline. In October 2022, pH ranged from 6.9 to 8.2, specific electrical conductance (PEW) ranged from 536 to 1717  $\mu\text{S}/\text{cm}$ , and dissolved oxygen ranged from 64.5 to 100.6 mg/L. In September 2023, pH ranged from 7.8 to 8.7 and PEW from 491 to 1230  $\mu\text{S}/\text{cm}$ . In October 2025, pH ranged from 7.56 to 8.05 and PEW from 879 to 1345  $\mu\text{S}/\text{cm}$ . Water temperatures ranged from 10.5 to 11.6 °C in October 2025 and from 12.4 to 25.8 °C in warmer-season campaigns. The slightly alkaline reaction and moderate mineralisation are consistent with shallow groundwater circulation through Quaternary sandy-gravelly deposits with calcareous cement. The elevated temperatures in summer/autumn campaigns and the rapid thermal equilibration with ambient air confirm that these are shallow-circulation waters with short aquifer transit times. No acidic drainage indicative of sulfide mineral oxidation was detected in any campaign, reflecting the essentially non-sulfidic clay lithology. The slight alkalinity (pH 7.6-8.7) is attributed to the dissolution of carbonate cements within Quaternary sands and gravels in the southern sector, rather than to any deep hydrothermal influence. In situ profiling was the measurement modality used to record all physicochemical parameters at the inflow points.

*Morphological Change and Slope Behaviour*

C2M difference maps revealed progressive internal reshaping in each monitoring interval (Tab. 2). In 2022–2023, two zones of accelerated vertical change were identified in the southern pit sector, both immediately above the contemporaneous water line: Sub-area #1 (ca. 6000 m<sup>2</sup>, maximum

vertical displacement  $\approx 1.5$  m) displayed characteristics of a translational slide whose snout reached the water surface, with the main scarp extending to approximately 192 m a.s.l.; Sub-area #2 (ca. 1500 m<sup>2</sup>) showed shallower instability across two benches directly beneath a seepage point, with a maximum vertical displacement  $\approx 1.1$  m. In 2023–2024, four zones of morphological change were documented, all in the southern sector, associated with bench-face sliding at individual extraction levels. In 2024–2025, eight change zones were identified, of which seven were of natural origin (primarily slope wash and sliding, concentrated in the southern sector) and one was anthropogenic (surface grading in the north-western portion of the mining area) (Figure 1).

Critically, in all four monitoring periods, no morphological change attributable to slope instability was detected along or outside the external pit rim (Worsa-Kozak *et al.* 2022–2025). All identified displacement zones were confined to interior pit faces at elevations that will be fully submerged as the lake continues to fill. The absence of external rim deformation is consistent with the geological control: the outer pit walls above the future maximum water level (ca. 200–201 m a.s.l.) are composed predominantly of firm, low-permeability Oligocene-Pliocene clay, which has not experienced significant changes in pore pressure during the monitored period. The internal instabilities are driven by: (i) concentrated groundwater seepage through the Quaternary sand-gravel unit outcropping in the southern faces, undercutting clay benches; and (ii) wave-action and waterline-parallel erosion as the lake surface rises. The slopes above the pit rim are not in direct hydraulic contact with the active seepage zone, because the thick clay series acts as

*Table 2 Summary of morphological change zones identified by Cloud-to-Mesh analysis, 2022–2025.*

Period	Change zones (total)	Natural origin	Anthropogenic origin	Location of changes
2022–2023	2	2	0	Southern sector, above waterline
2023–2024	4	4	0	Southern sector, bench faces
2024–2025	8	7	1	Southern + eastern; NW grading



an aquitard. Nonetheless, the water-balance model (Worsa-Kozak *et al.* 2023) identified the northern pit rim (ca. 200-201 m a.s.l.) as the lowest-elevation sector; therefore, long-term monitoring of that rim remains warranted.

### Volumetric Change and Initial Pit-Lake Morphology

The total void volume of the excavation above the 2022 baseline level (171.98 m a.s.l.) is ca.  $9.79 \times 10^6 \text{ m}^3$ , as derived from the 2022 photogrammetric survey. Between 2024

and 2025, the flooded volume increased by ca.  $370\,000 \text{ m}^3$  (Scenario 2:  $124\,885 \text{ m}^3$  of net geometric change attributable to morphological adjustment, excluding the flooded volume). The excavation hypsometry shows a bowl-shaped profile: bathymetric cross-sections in the SW-NE and NW-SE directions demonstrate near-vertical to steeply dipping walls down to ca. 170–175 m a.s.l., widening progressively upward. The minimum rim elevation in the northern sector is ca. 200–201 m a.s.l., defining the maximum feasible lake level.

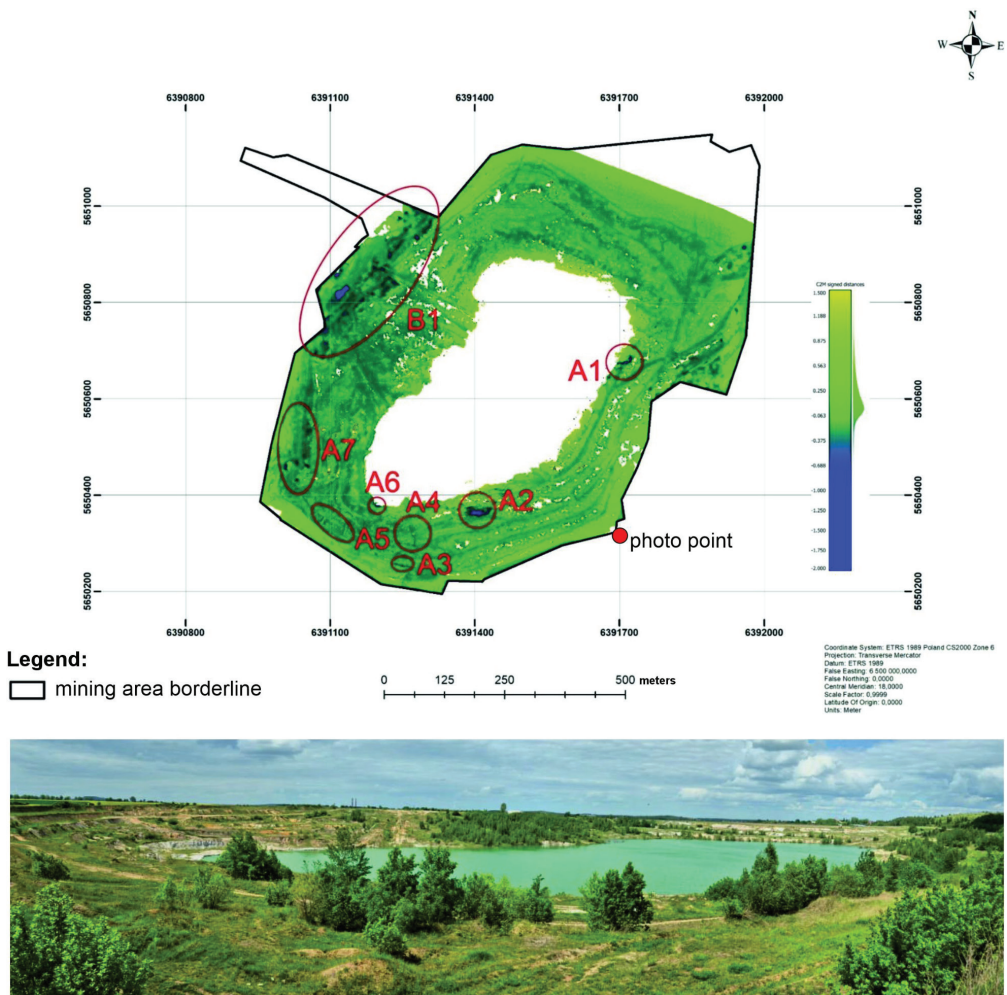


Figure 1 The results of the difference analysis showing morphological changes 2024-2025 in the reclaimed excavation area. Locations of visible morphological changes: (A) of natural origin; (B) of anthropogenic origin. Source: Worsa-Kozak *et al.*, 2022-2025, Photo by: M. Worsa-Kozak.



The initial pit-lake morphology at 177.23 m a.s.l. (October 2025 water level) shows an elongated, asymmetric basin. The deepest accessible area is in the central-northern zone, while the southern zone features the active seepage faces and erosion scarps. As the lake level rises, the water surface will progressively cover the lower benches of the southern wall, reducing exposed seepage-face area and likely moderating internal erosion. The development of a shoreline morphology through wave action and nearshore erosion is already visible in the 2025 difference map (Figure 1) along the northern waterline. A quantitative hypsometric curve was available from the 2022 photogrammetric baseline survey and served as the basis for the water-balance model calculations.

#### *Water Balance: Model Validation*

The Water balance model (Worsa-Kozak *et al.* 2023) is based on: (i) annual precipitation data from Dobrogoszcz station (1956-2022); (ii) actual evapotranspiration estimated by Pardé nomogram using a mean annual temperature 9.2 °C; (iii) groundwater inflow measured at field campaigns; and (iv) the excavation hypsometry from UAV photogrammetry. The four-year observed record now available constitutes the first empirical validation dataset for this model, and its expansion will enable progressive refinement of the inflow parameters. The 2023 water-balance forecast (Worsa-Kozak *et al.* 2023) predicted annual water storage increase ( $\Delta R$ ) of 57 084 m<sup>3</sup>/a (Scenario III, low precipitation), 126 780 m<sup>3</sup>/a (Scenario II, mean precipitation), and 249 548 m<sup>3</sup>/a (Scenario I, high precipitation). The predicted water-level rise for Scenario II from the baseline of 172 m a.s.l. was approximately 1 m in the first year. Observed rises of 0.97 m (Year 1) and 2.11 m (Year 2) are consistent with Scenario II and Scenario I, respectively, suggesting that 2023-2024 was a significantly wetter-than-average period. The long-term neutral-scenario forecast of ca. 59 years to reach 200 m a.s.l. remains a reasonable central estimate.

#### **Discussion**

The Stanisław-Południe case demonstrates that integrated UAV photogrammetry and

hydrogeological mapping provide a cost-effective, technically robust approach for real-time monitoring of pit-lake formation. The methodology is replicable at comparable post-mining sites and offers regulatory authorities evidence-based documentation of slope behaviour and water-body formation, as required by Polish mining reclamation law.

The accelerating filling rate observed after 2023 (from ca. 1 m/a to ca. 2.1–2.2 m/a) is an important departure from the initially estimated neutral-scenario rate. Two factors may explain this acceleration. First, as the lake surface area expands with rising water level, the effective precipitation catchment area increases proportionally, augmenting direct recharge. Second, submerged seepage faces contribute to the hydraulic head balance in ways not fully captured by surface-only inflow measurements. Once seepage points fall below the water surface, their discharge is no longer directly measurable, but they continue to contribute to lake volume. The good agreement between the observed Year 1 rise and the Scenario II prediction confirms the model's validity under average conditions. In contrast, the Year 2-4 acceleration suggests that wetter-than-average conditions or the progressive expansion of the effective recharge area should be incorporated into future model updates, as recommended by Worsa-Kozak *et al.* (2023) at 5-year intervals.

The internal slope instabilities documented in each monitoring period are geotechnically consistent with the hydrogeological setting. The southern pit wall, where the Quaternary aquifer directly contacts the excavation face through a ca. 10 m saturated sand-gravel unit, experiences the highest pore-pressure gradient. As the pit lake rises, the saturated thickness between the lake water surface and the free-water table in the southern aquifer decreases, reducing the hydraulic gradient and, consequently, the seepage velocity. This mechanism predicts a self-limiting character to the southern-wall instabilities: as the lake approaches equilibrium with the surrounding groundwater table, seepage forces will diminish. The consistently observed absence of deformation at the outer pit rim supports this interpretation. It is physically explained



by the presence of the thick, low-permeability Oligocene-Pliocene clay series, which isolates the outer rim from the hydraulically active southern aquifer.

Based on the four years of data, the monitoring and geotechnical analyses indicate potential future slope stability beyond the mining area borderline. The outer-rim geology (firm clays, low hydraulic conductivity, minimal pore-pressure change) and the absence of any measurable surface displacement along the rim in any campaign support this conclusion. However, it is acknowledged that pore-pressure monitoring within the outer-rim embankment has not been conducted; this constitutes a limitation of the current monitoring scope. Installation of piezometers in the outer rim area would provide a more definitive assessment of this risk.

The water chemistry data reveal a consistent pattern of slightly alkaline, low-TDS groundwater with no indication of acid generation, consistent with the absence of reactive sulfide minerals in the clay lithology. The elevated summer campaign temperatures (up to 25.8 °C at P8 in September 2023) reflect the short subsurface residence time of near-surface recharge water during warm periods rather than any anthropogenic thermal influence. The seasonally variable chloride concentrations (range 77-279 mg/L) are consistent with agricultural land use in the catchment (fertiliser application) and road de-icing.

## Conclusions

Four years of integrated UAV photogrammetric and hydrogeological monitoring at the Stanisław-Południe pit lake have yielded the following principal findings:

(I) Water levels rose cumulatively by 5.25 m (from 171.98 m a.s.l. in 2022 to 177.23 m a.s.l. in 2025), with the annual rise accelerating from ca. 1 m/a in 2022-2023 to ca. 2.1 m/a in 2023-2025, broadly consistent with the neutral to wet precipitation scenarios of the water-balance model. (II) Eight active inflow points were identified in October 2025, supplying a total of 2.34 L/s. Inflow waters are consistently slightly alkaline (pH 7.56-8.05 in 2025), with moderate mineralisation

(PEW 879-1345  $\mu\text{S}/\text{cm}$ ), characteristic of shallow Quaternary aquifer circulation with no indication of acid-mine drainage. (III) Internal slope reshaping is ongoing, with a progressive increase in identified change zones. All instability is confined to benches destined for submersion in the southern and eastern pit sectors; the external pit rim remains unaffected. (IV) The absence of outer-rim deformation is attributable to the isolating effect of the thick Oligocene-Pliocene clay series, which prevents hydraulic connection between the active southern aquifer and the outer-rim slope. (V) The 2023 water-balance model is validated as broadly accurate for the first year of observation and points to wetter-than-average conditions or an increasingly effective catchment area as explanations for the post-2023 acceleration. (VI) The integrated UAV-geomatics plus hydrogeological methodology constitutes a replicable reference framework for monitoring flooded post-mining excavations in Central European geological settings.

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