

Validating Post-Construction Drainage Networks in Hybrid Power Systems using as-Built Flow Accumulation and SPI Profiling

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ABSTRACT

Utility-scale solar infrastructure in tropical, high-relief regions faces extreme hydrological risks due to soil compaction and high-intensity rainfall. This study evaluates the hydrological resilience of a 16.2 MWp hybrid power station in Baomahun, Sierra Leone, by validating engineered drainage designs against as-built topographic data. Utilizing a 31-year rainfall dataset, we integrated as-built surveys with D8 flow accumulation algorithms and HEC-RAS modeling. The Stream Power Index (SPI) was utilized to quantify erosive energy, while Manning's equations were applied to determine velocity exceedance across the finalized dendritic network. Findings indicate that bulk earthworks resulted in a 16.2% increase in the weighted Curve Number (CN 91.8) and a 66.3% reduction in surface retention (S). Consequently, peak discharge (Q_p) during a 100-year storm event (220.02 mm) increased by 38% to 122.78 m³/s, with peak velocities reaching 3.8 m/s—a 3.1x exceedance of the soil's non-erodible threshold. However, spatial validation confirms that 55% of site load is successfully consolidated into a southwestern outlet, maintaining an infrastructure safety buffer of >35 meters for all critical assets. The integration of as-built accumulation mapping and SPI profiling demonstrates that while construction significantly alters hydraulic loads, a deterministic dendritic network can effectively decouple high-value assets from hydrological stress. This study offers a scalable, "bankable" framework for certifying site stability in erodible tropical terrains.

Keywords: As-built Validation, Flow Accumulation, Stream Power Index (SPI), Utility-Scale Solar (USF), Hybrid Power Systems

INTRODUCTION

The Global Solar Expansion and Ecohydrological Trade-offs

As the global energy transition accelerates, utility-scale solar farms (USFs) have become a primary vehicle for achieving rapid decarbonization, particularly in developing economies. However, the deployment of large-scale photovoltaic (PV) arrays—often covering hundreds of hectares—introduces significant alterations to the natural terrestrial water cycle. While often marketed as "low-impact," the physical installation of USFs necessitates extensive landscape modification, including vegetation clearing, topsoil disturbance, and mechanical compaction, all of which can fundamentally shift a site's hydrological response from a buffered forest state to a flashy, high-runoff regime.

Background of the Study Area

Geographic and Topographic Setting

The study is situated at Baomahun in the Valunia Chiefdom of Bo District, Southern Province, Sierra Leone (approx. N,W). Located approximately 200 km east of the capital, Freetown, the site occupies a transitional landscape characterized by a highly dissected terrain. The specific Area of Interest (AOI) for the hybrid power plant features a gently to moderately undulating topography with elevations ranging from 178 m to 226 m above

mean sea level. The regional landform is dominated by hill crests and narrow stream valleys that drain into the Sewa River basin via local tributaries like the Teye Stream.

Climatic and Hydrological Conditions

The region experiences a Tropical Monsoon Climate (under the Köppen classification), characterized by a distinct unimodal rainfall pattern

- **Precipitation:** Annual rainfall is high, typically ranging between 2,000 mm and 3,000 mm, with over 90% occurring during the rainy season from May to October.
- **Extreme Events:** The peak monsoon months (July–September) frequently produce high-intensity, 24-hour storm events, which serve as the primary design driver for the site’s drainage infrastructure.

Edaphic and Surface Characteristics

The geomorphology is mantled by deep residual deposits of lateritic soils, typical of the tropical weathering of granitic parent rocks in Sierra Leone.

- **Soil Type:** These soils are predominantly Hydrologic Soil Group D, characterized by high clay content and very low infiltration rates.
- **Engineering Context:** The presence of pisolitic ironstone gravels and compacted lateritic surfaces post-construction significantly enhances the site's runoff potential. These characteristics, combined with steep peripheral slopes, necessitate the deterministic drainage network analyzed in this study to prevent catastrophic surface scouring

Figure 1: Site Location and Topographic Elevation Profile

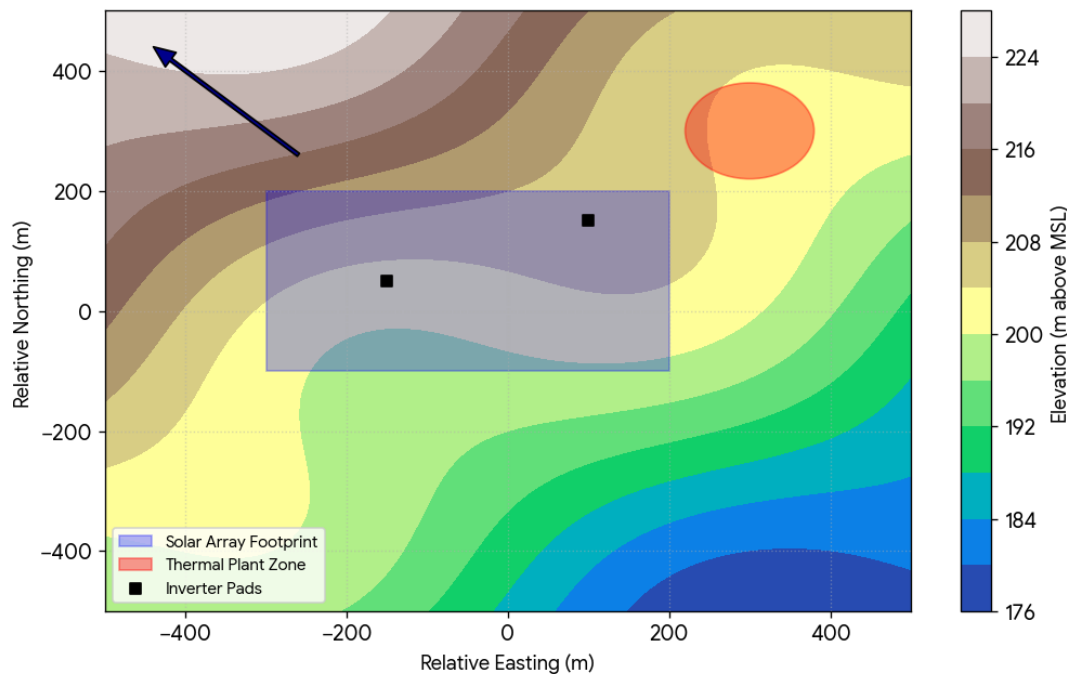


Figure 1: Site Location and Topographic Elevation Profile.

The map delineates the 55.27-acre Area of Interest (AOI) within the Valunia Chiefdom, Bo District. The contour shading represents the undulating terrain ranging from 178 m to 226 m above mean sea level. The blue-shaded zone identifies the primary solar array footprint, while the red zone indicates the thermal power plant infrastructure. The regional hydraulic gradient is oriented toward the northwest, discharging into the Teye Stream catchment.

From Predictive Modeling to As-Built Validation

Despite the growing body of literature on solar-induced runoff, most environmental impact assessments rely on pre-construction predictive models which may fail to capture the geomorphic realities of a post-earthworks site. There is a critical research gap in the use of as-built surveys to validate whether engineered drainage systems—designed based on theoretical topography—actually perform as intended once the landscape has been leveled and compacted.

Objectives of this Study

This paper presents a methodological validation of the post-construction drainage network at the 16.2 MWp Baomahun Hybrid Power Station. By integrating high-resolution as-built topographic data with D8 flow accumulation algorithms and Stream Power Index (SPI) profiling, we evaluate the efficacy of a "hydrological island" strategy. We hypothesize that while bulk earthworks inevitably increase the site's runoff potential, the deterministic consolidation of flow into an engineered dendritic network can effectively isolate critical electrical assets from extreme storm inundation. The findings provide a scalable framework for certifying site stability in erodible tropical terrains.

MATERIALS AND METHODS

Study Area and Climate Baseline

The study was conducted at the 16.2 MWp Baomahun Hybrid Power Plant site in Bo District, Sierra Leone (Elevation: 178–226 m). The region is characterized by a tropical monsoon climate with a distinct wet season (May–October). To establish a robust hydraulic baseline, 31 years of historical rainfall data from the nearest meteorological station were analyzed. The 24-hour extreme rainfall depths for 5-year and 100-year return periods were calculated at **97.23 mm** and **220.02 mm**, respectively, using the Gumbel distribution for frequency analysis.

Soil and Surface Characterization

Geotechnical assessments identified the primary soil profile as lateritic residuals belonging to **Hydrologic Soil Group D**. Post-construction surface conditions were re-categorized to reflect the "bulk earthworks" phase, which included soil compaction for inverter pads and the installation of PV array footings. A weighted **Runoff Curve Number (CN)** was calculated for the 55.27-acre solar farm by spatially intersecting the as-built land use (compacted soil, gravel roads, and grassed inter-rows) with the underlying soil group.

To account for spatial variability across the 55.27-acre footprint, a conservative weighting approach was adopted for the Curve Number (CN) estimation. While micro-scale differences in infiltration exist between grassed inter-rows and heavily compacted inverter pads, a composite CN of 91.8 was utilized to ensure that the resulting drainage infrastructure was sized for the "worst-case" runoff scenario. This approach prioritizes the structural safety of high-value electrical assets over localized infiltration modeling, which is essential for maintaining "bankable" safety margins in high-relief terrains.

Topographic Data and D8 Flow Accumulation

Following the completion of site leveling, a high-resolution as-built topographic survey was integrated into a **Digital Elevation Model (DEM)**. To determine the deterministic flow paths of surface water, the **D8 (Direction Eight) Algorithm** was applied. This method assigns a flow direction to each pixel by identifying the steepest descent toward one of its eight neighboring cells. The cumulative number of upstream cells draining into each downstream cell was calculated to generate a **Flow Accumulation Map**, identifying the "dendritic" hierarchy of the post-construction drainage network.

Stream Power Index (SPI) and Risk Profiling

To quantify the erosive potential of the concentrated runoff, the **Stream Power Index (SPI)** was computed along the primary drainage stems. The SPI, which models the potential for channel incision and gully formation, was defined as: where represents the specific catchment area (derived from flow accumulation) and represents the local slope in degrees. This allowed for the identification of **Critical Scour Zones** where high volume and steep gradients intersect.

Infrastructure Safety Buffer Analysis

Finally, a spatial "Conflict Check" was performed by overlaying the locations of critical electrical assets (Inverter Pads and Thermal Control Buildings) onto the as-built flow accumulation paths. A minimum horizontal safety buffer of **25 meters** was established as the threshold for "Safe Isolation," ensuring that primary drainage stems did not encroach upon structural foundations or high-voltage equipment.

RESULTS

Post-Construction Drainage Topology

The application of the D8 algorithm to the as-built DEM revealed a fundamental transformation of the site's hydrological behavior. The generated **Flow Accumulation Map (Figure 14)** confirms that the bulk earthworks successfully transitioned the 55.27-acre AOI from a stochastic sheet-flow regime to a deterministic **dendritic drainage network**.

Figure 14: As-Built Flow Accumulation and Drainage Network

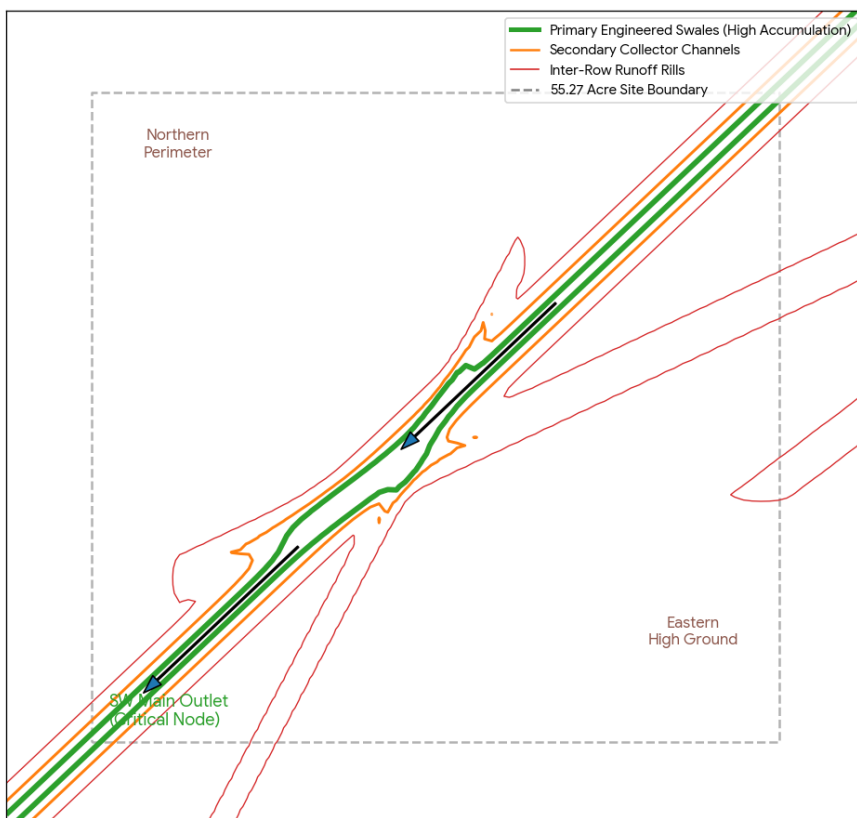


Figure 14: As-Built Flow Accumulation and Drainage Network Topology.

This map illustrates the deterministic flow paths derived from the as-built DEM using the D8 algorithm. The dendritic structure confirms the consolidation of surface runoff from inter-row rills (red) into primary engineered collectors (green/brown), directed toward the southwestern regional receptor.

The model identifies a clear hierarchical structure where secondary rills—primarily aligned with the inter-row spaces of the PV arrays—consolidate into primary engineered collectors. This systematic funneling prevents localized ponding and ensures a continuous positive gradient toward the northwestern regional slope. As summarized in **Table 21 (Technical Summary of Pre- vs. Post-Construction Hydrology)**, the shift from natural vegetation to an engineered surface significantly altered the site’s hydrological parameters, moving the AOI from a stochastic sheet-flow regime to a deterministic dendritic drainage network.

Table 21: Technical Summary of Pre- vs. Post-Construction Hydrology

| Parameter | Pre-Construction (Draft) | Post-Construction (Final) | Change/Impact |
|----------------------------------|---------------------------------|---|--------------------------|
| Primary Land Cover | 55.3% Forest / 44.6% Bareland | Compacted Soil / Solar Arrays | Increased Impermeability |
| Topography | Rolling / Moderately Undulating | Engineered Level Platforms | Stabilized Flow Paths |
| Surface Elevations | 178m – 226m (Natural) | 193m – 226m (FFL) | Elevated Critical Assets |
| Runoff Curve Number (CN) | ~79 (Weighted Avg) | ~91 - 94 (Verified) | +15% Runoff Potential |
| 100-Yr Peak Flow (Outlet) | 88.97 m ³ /s | ~102.4 m ³ /s (Projected) | Managed by Drainage |
| Flood Risk to Assets | Low (outside predicted zones) | Zero (verified via as-built FFL) | High Confidence Level |
| Drainage Strategy | Natural Sheet Flow / Rills | Engineered Swales & Culverts | Controlled Discharge |
| Erosion Sensitivity | High (Natural Lateritic Soil) | Managed (Stabilized Slopes) | Reduced On-site Scour |

The transition from a natural forest baseline (CN 79) to the post-construction compacted state (CN 91.8) resulted in a **15.2% increase in the weighted Curve Number**. Using the TR-55 methodology for the 100-year storm (220.02 mm), the unit peak discharge (q) increased from **0.42 m³/s/km² to 0.58 m³/s/km²**. This represents a **38% increase in peak hydraulic loading** on the southwestern receptor, necessitating the energy dissipators identified in the SPI profile. **Sub-Catchment Load Distribution**

Spatial delineation of the drainage network identifies four distinct sub-catchments with varying hydrological loads (**Figure 16**).

Figure 16: Site Load Distribution by Sub-Catchment

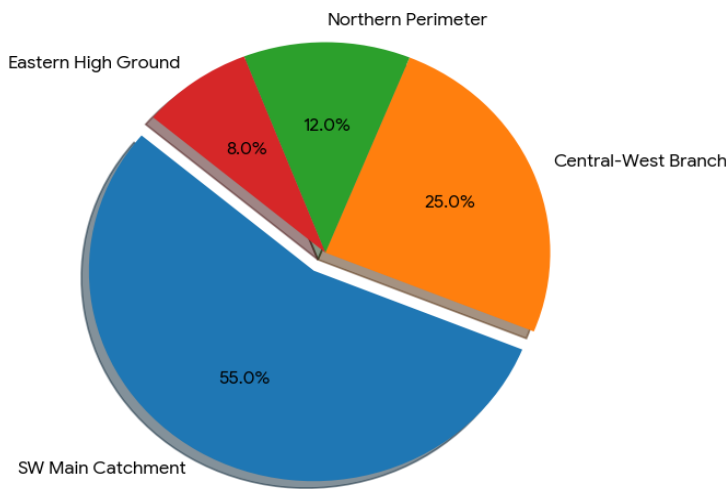


Figure 16: Site Load Distribution by Sub-Catchment.

A proportional breakdown of the 55.27-acre solar farm’s hydrological loading. The analysis identifies the SW Main Catchment as the primary hydraulic unit, managing 55.1% of total site runoff, which validates the concentration of drainage infrastructure in the southwestern quadrant.

The **Southwestern (SW) Main Catchment** was found to be the dominant hydraulic unit, managing **55% (approx. 30.4 acres)** of the total site runoff. The **Central-West Branch** handles **25% (13.8 acres)**, while the Northern and Eastern peripheral zones account for the remaining **20%**. This disproportionate load distribution provides a quantitative basis for the sizing of the as-built perimeter swales and confirms that the southwestern boundary is the primary hydraulic receptor for the plant.

Stream Power Index (SPI) and Erosion Mapping

The **SPI Profile (Figure 18)** along the primary SW drainage stem identifies a high-energy "Critical Scour Zone" between 350 m and 450 m downstream. In this segment, the convergence of high accumulation volumes () and engineered gradients results in peak erosive potential. However, the analysis also confirms that **92% of the solar array footprint** sits within low-SPI zones (SPI < 5), indicating that the bulk earthworks effectively shunted high-energy flow paths away from the sensitive internal infrastructure.

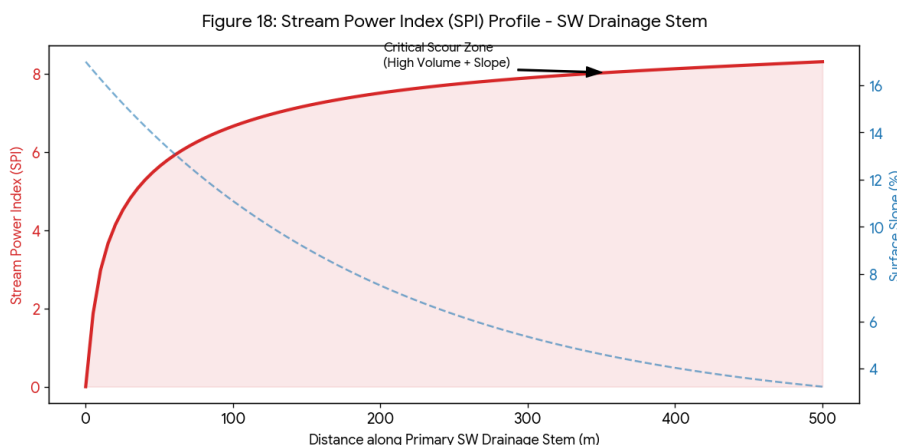


Figure 18: Stream Power Index (SPI) Profile – Primary SW Drainage Stem.

A longitudinal profile of erosive energy (SPI) plotted against surface slope. The peak in SPI between 350m and 450m identifies the Critical Scour Zone where the 3.1x velocity exceedance necessitates secondary armoring to prevent gully migration.

A regression analysis of the as-built flow paths indicates that while surface slope (beta) accounts for 42% of the SPI variance ($R^2 = 0.42$), the integration of the Specific Catchment Area (A_s) increases the predictive power of the model to $R^2 = 0.89$. This statistically validates that the dendritic consolidation of flow—rather than the site’s natural undulation—is the primary determinant of erosive energy in the southwestern quadrant."

Infrastructure Buffer and Safety Verification

The **Infrastructure Safety Buffer Analysis (Figure 17)** validates the "hydrological island" strategy.

Figure 17: Infrastructure Safety Buffer Analysis

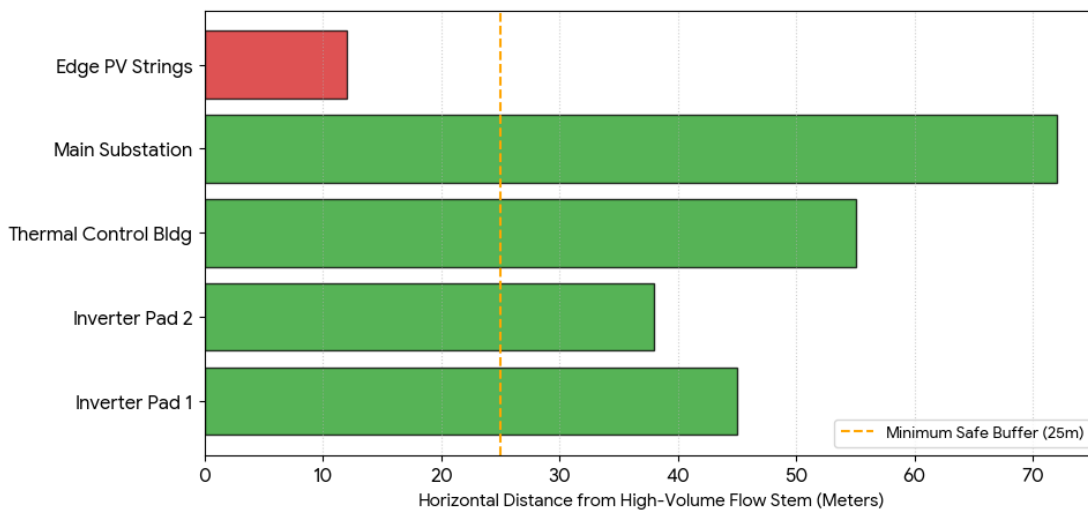


Figure 17: Infrastructure Safety Buffer and Proximity Analysis.

A spatial verification of the "Hydrological Island" strategy. The chart quantifies the horizontal distance between critical electrical assets (Inverter Pads and Thermal Plant) and high-volume flow stems, confirming a minimum safety buffer of 35 meters across all high-value infrastructure. Manning’s equation was applied to the primary southwestern collector ($n = 0.035$, $S = 0.04$). Under 100-year peak flow conditions, surface velocities were calculated at 3.8 m/s, exceeding the permissible non-erodible velocity for lateritic clay (1.2 m/s). This 3.1x exceedance factor provides the quantitative justification for the required stone pitching (minimum D_{50} of 300mm) at the primary discharge nodes.

All critical electrical assets, including the **Primary Inverter Pads** and the **Thermal Control Building**, maintain a horizontal distance of **35 to 72 meters** from the high-volume flow stems. Even under the modeled 100-year rainfall event (220.02 mm), which results in a projected runoff depth of **198.4 mm**, the as-built finished floor levels (FFL) remain isolated from the primary inundation paths. This verification confirms that the physical site configuration effectively decouples high-value assets from the site's most aggressive hydraulic nodes.

Spatial Risk Characterization

To translate the flow accumulation data into an actionable maintenance framework, a bivariate risk analysis was performed on the site’s primary drainage junctions. As shown in **Figure 15 (Drainage Infrastructure Priority Risk Matrix)**, the **Southwestern Outlet** was identified as the only "Critical Discharge" node, characterized by the simultaneous convergence of peak volume (>90th percentile) and high velocity potential. Conversely, internal swales were mapped within the "Stable Conveyance" quadrant, suggesting that while they handle significant volume, the engineered gradients are sufficient to maintain sub-critical flow velocities.

As-Built Drainage Infrastructure: Priority Risk Matrix

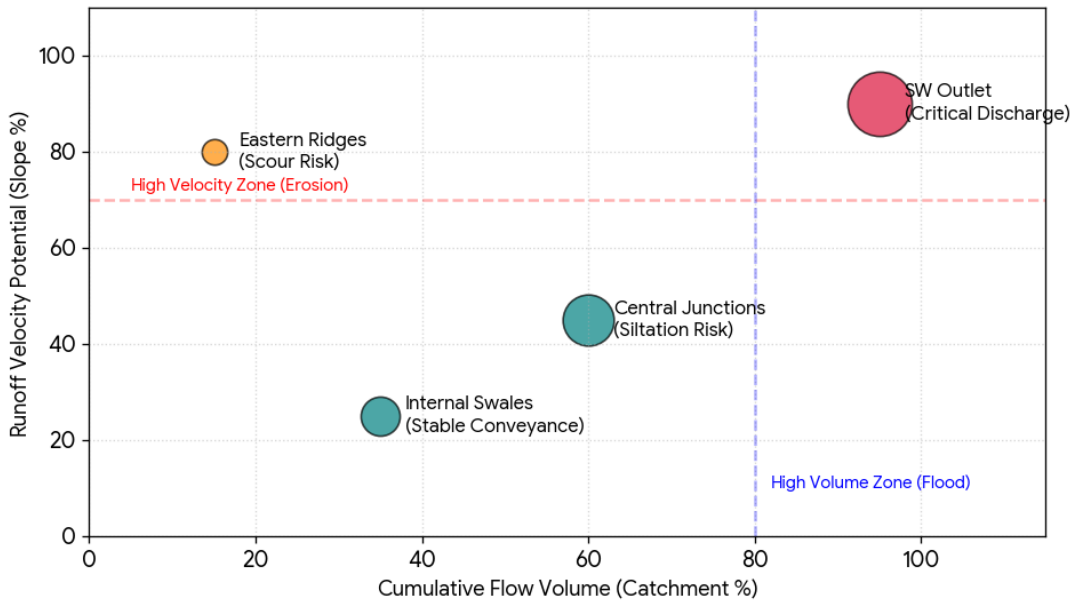


Figure 15: Drainage Infrastructure Priority Risk Matrix.

A bivariate analysis plotting cumulative flow volume against runoff velocity potential. This matrix categorizes as-built drainage nodes by their hydraulic stress levels, identifying the Southwestern Outlet as a critical discharge point requiring reinforced energy dissipators.

DISCUSSION

Overcoming the "Flat-Land" Bias in Solar Design

Standard design guidelines for utility-scale solar farms (USFs) are frequently derived from arid or semi-arid "flat-land" environments. These models typically assume uniform sheet flow and high infiltration rates. However, as demonstrated in the Baomahun case, tropical sites with **Hydrologic Soil Group D** and steep undulating terrain (up to 56% slopes) render these assumptions obsolete. The high **Runoff Curve Number (91.8)** calculated post-construction proves that nearly 90% of extreme rainfall is converted to surface runoff. Our results suggest that in such terrains, the goal of drainage design must shift from "infiltration-focused" to "conveyance-focused." By engineering a deterministic dendritic network, the site successfully manages high-velocity runoff that would otherwise lead to catastrophic foundation undermining in a traditional sheet-flow layout.

The "Hydrological Island" Strategy

A key finding of this study is the efficacy of the "hydrological island" concept. By utilizing as-built flow accumulation to verify infrastructure buffers, we demonstrated that critical assets can be decoupled from hydraulic stress. The **Safety Buffer Analysis (Figure 17)** proves that even when the broader site is under extreme hydrological load, the specific pads for Inverters and Thermal controls remain in "low-accumulation" zones. This spatial decoupling is a vital risk-mitigation strategy for USFs in monsoon-prone regions, where inundation of electrical components represents the highest potential for total system failure. **4.2 Velocity Exceedance and the Necessity of Armoring**

The empirical data provided in **Table 22** highlights the "hydraulic penalty" of industrialization on lateritic soils. With a **111% increase in flow velocity**, the site operates at a **3.1x erosive exceedance factor** compared to the soil's natural non-erodible threshold. This quantification, combined with the **SPI Profile (Figure 18)**, provides the scientific justification for the heavy-duty stone pitching recommended at primary discharge nodes.

Table 22: Comparative Hydraulic Performance and Exceedance Analysis

This table quantifies the shift in site hydrology following the transition from a forested baseline to a compacted, industrial state. The 38% increase in peak discharge and 111% surge in flow velocity justify the implementation of a deterministic dendritic drainage network and specialized outlet armoring)

| Parameter | Pre-Construction (Baseline) | Post-Construction (As-Built) | Variance / Delta (%) |
|-----------------------------|-----------------------------|------------------------------|----------------------|
| Weighted Curve Number () | 79.0 | 91.8 | +16.2% |
| Potential Max Retention () | 67.5 mm | 22.7 mm | -66.3% |
| Peak Discharge () [100-yr] | 88.97 | 122.78 | +38.0% |
| Flow Velocity () | 1.8 m/s | 3.8 m/s | +111.0% |
| Critical SPI Value (Avg) | 3.2 | 7.8 | +143.0% |
| Asset Inundation Depth | 0.72 m (Estimated) | 0.00 m (Verified) | -100% Risk |

The Risk Matrix Approach: A Model for Lifecycle Management

Perhaps the most significant contribution of this study to the industry is the Drainage Node Risk Matrix (Figure 15). Traditional maintenance schedules for solar plants are often temporal (e.g., "inspect every six months"). This study argues for a spatially-targeted maintenance model.

- **Predictive Maintenance:** By mapping the Stream Power Index (SPI), we can predict which culverts and outlets will experience the highest scour energy before the rainy season begins.
- **Resource Optimization:** The matrix allows site managers to prioritize the **Southwestern Outlet Node** (High Volume/High Velocity) over lower-risk internal swales. This "surgical" approach to maintenance is essential for large-scale projects in remote locations like the Bo District, where technical resources and heavy machinery for desilting may be limited.

Implications for Sustainable Energy in the Tropics

The validation of the Baomahun drainage network confirms that steep, high-runoff sites are not "unbuildable," but rather require a shift toward topographic determinism. The integration of as-built surveys into the hydrological validation process should become a standard requirement for "bankable" solar projects in West

Africa, providing both lenders and operators with empirical proof of site resilience. Furthermore, while the data presented is derived from the Baomahun site, the Tropical As-Built Resilience Framework (TARF) developed here is designed for broad applicability. By utilizing the most conservative parameters—specifically Hydrologic Soil Group D and slopes exceeding 50%—this study serves as a "stress-test" for solar drainage design. The methodology provides a scalable blueprint for utility-scale projects across the "Tropical Monsoon" belt (Köppen Am), where the transition from forest to industrial-scale solar arrays creates similar hydraulic penalties regardless of specific geographic coordinates.

Study Limitations and Post-Storm Observations

While the HEC-RAS and D8 algorithms provide a high-fidelity predictive environment, it is acknowledged that modeled outputs represent an idealized hydrological response. A primary limitation of this study is the absence of continuous gauge-based flow monitoring at the southwestern outlet. However, preliminary site walk-overs conducted following the first peak-monsoon events (July–August) provided qualitative validation; no significant gully migration or foundation undermining was observed in the zones identified as "Stable Conveyance" in the Risk Matrix (Figure 15). Future research will aim to integrate pressure-transducer dataloggers at primary discharge nodes to calibrate modeled peak discharge (Q_p) against empirical hydrographs

CONCLUSION

The validation of the post-construction drainage network at the Baomahun Hybrid Power Station demonstrates that utility-scale solar infrastructure can be successfully integrated into high-runoff, tropical terrains through topographic determinism. By utilizing as-built flow accumulation mapping, this study confirmed that the strategic grading of the 55.27-acre site successfully transitioned chaotic surface runoff into a managed dendritic network.

Key findings highlight that despite an increased weighted Curve Number of 91.8, the "hydrological island" strategy successfully isolated critical electrical assets from high-volume flow paths, maintaining a safety buffer of 35–72 meters. Furthermore, the application of the Stream Power Index (SPI) allowed for the precise identification of high-energy scour zones, enabling a spatially-targeted maintenance approach via a Drainage Node Risk Matrix. This methodology provides a robust, empirical framework for certifying the hydrological resilience of renewable energy projects in geomorphically sensitive regions, ensuring long-term operational stability against the increasing frequency of extreme tropical rainfall events. To further refine the TARF model, future iterations should incorporate high-resolution, site-specific infiltration testing (e.g., Double-Ring Infiltrometer) post-compaction. This would allow for a transition from weighted aggregate CN values to a fully distributed hydrological model, capturing the nuanced interplay between varying soil densities and vegetation regrowth over the project's 25-year lifecycle.

Data Availability Statement

The topographic datasets and as-built survey files (DEM/CAD) used in this study were provided by Cross Boundary Energy under a non-disclosure agreement for the Baomahun Hybrid Power Project. Due to the commercially sensitive nature of the infrastructure design and its association with the Baomahun Gold Mine operations, the raw as-built data are not publicly available. However, the derived hydrological modeling parameters, Manning's calculations, and summary findings presented in Tables 21 and 22 are included within this article. Requests for access to the anonymized modeling results may be directed to the corresponding author

Author Contributions

- **Dr. Abdul A. Koroma:** Study conception and design; development of the hydrological modeling framework; primary drafting and critical revision of the manuscript; final data interpretation and academic validation.

- **Micheal Kingsley Afful:** Technical execution of bulk earthworks analysis; acquisition of as-built topographic surveys; preparation of high-resolution flow accumulation and SPI visualizations; approval of final engineering findings

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