

Enset (Ensete ventricosum) as a Nature-Based Hydrological Intervention: A Process-Based Framework for Rainfall Partitioning, Direct-Runoff Regulation, and Flood Mitigation in the Upper Awash Basin, Ethiopia.

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Enset (*Ensete ventricosum*) as a Nature-Based Hydrological Intervention: A Process-Based Framework for Rainfall Partitioning, Direct-Runoff Regulation, and Flood Mitigation in the Upper Awash Basin, Ethiopia.

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Abstract

Nature-based solutions (NBS) are increasingly recognized as complements to conventional flood-control, yet their hydrological effectiveness depends strongly on how vegetation modifies rainfall partitioning, storage, infiltration, and runoff generation. In the Ethiopian highlands, Enset (*Ensete ventricosum*) a perennial food-security crop-possessed a distinctive architecture that may influence rainfall-runoff processes, but its hydrological function has rarely been represented explicitly in catchment-scale models.

This study develops process-oriented ecohydrological framework that represents Enset as a hydraulic component of the rainfall-runoff system rather than solely as a land-cover class. The model explicitly accounts for leaf storage, midrib conveyance, stemflow concentration, and enhanced infiltration. The remaining non-Enset area is represented using an Analytic Hierarchy Process (AHP) loss formulation, expressed as $L=0.40I+0.25D+0.15S+0.12E+0.08INT$. Enset and non-Enset runoff pathways are subsequently combined through area weighting. We implemented the framework using observations from the Holeta catchment, integrating HEC-HMS with machine learning validation.

For the 0% Enset baseline, the model achieved $NSE = 0.652$, $KGE = 0.758$, $(R^2) = 0.655$, $RMSE = 2.138 \text{ m}^3 \text{ s}^{-1}$, $PBIAS = 5.46\%$, and $MAE = 0.938 \text{ m}^3 \text{ s}^{-1}$ during calibration. Independent validation produced $NSE = 0.611$, $KGE = 0.718$, $(R^2) = 0.616$, $RMSE = 2.362 \text{ m}^3 \text{ s}^{-1}$, $PBIAS = 9.76\%$, and $MAE = 1.004 \text{ m}^3 \text{ s}^{-1}$. Increasing Enset cover from 0% to 75% of the cropped area reduced modeled direct runoff by 13.5-67.5% Q95 flows by 13.5–67.6%, indicating substantial flood-regulation potential.

The results indicate that Enset cover can substantially modify catchment direct runoff through the combined effects of rainfall interception, hydraulic redistribution, stem-zone concentration, and enhanced infiltration. However, the modeled dynamic ring-storage filling ratio was very low, indicating that storage activation remains an important uncertainty. The study demonstrates the value of explicitly representing plant architecture in ecohydrological models and provides a basis for evaluating Enset-based land management as a complementary nature-based approach to flood-risk reduction in the Ethiopian highlands.

Keywords: Enset; *Ensete ventricosum*; ecohydrology; stemflow; rainfall partitioning; direct runoff; nature-based solutions; flood mitigation; Upper Awash Basin; HEC-HMS; AHP

1. Introduction

Flood risk in Ethiopia is shaped by the interaction of intense seasonal rainfall, land degradation, changing land cover, topography, and increasing exposure of people and infrastructure[1]. The Ethiopian highlands are particularly important because they supply water to major downstream river systems, including the Awash Basin, while simultaneously experienced recurrent wet-season runoff and flooding[2–5]. These challenges have traditionally been addressed through structural measures such as dams, levees, drainage improvements, and channel modifications[6,7]. Although such infrastructure remains important, increasing attention is being given to nature-based solutions (NBS) [6] that can complement conventional engineering by modifying hydrological processes within the landscape.

Vegetation can influence runoff through several interacting mechanisms. Canopies intercept rainfall, temporarily store water, alter the spatial distribution of throughfall, generate stemflow, increase surface roughness, and modify soil hydraulic conditions through root development and organic -matter inputs [8–12]. These processes affect not only the amount rainfall reaching the soil but also the location, intensity, and timing of water delivery. Consequently, vegetation should not necessarily be represented only through a single runoff coefficient or land-cove parameter when its architecture creates distinctive hydrological pathways.

Stemflow is particularly important in this context. Water captured by leaves can be transferred along leaf surfaces and stems and concentrated near the plant base [9,11,13,14]. This process may increase local rainfall intensity substantially while simultaneously creating a focused opportunity for infiltration. The resulting hydrological response depends on the balance between water

concentration and the infiltration capacity of the receiving soil [15]. Consequently, stemflow should be regarded primarily as a rainfall-redistribution mechanism rather than as runoff itself.

Previous studies of banana (*Musa* spp.) have demonstrated the importance of vegetation-mediated rainfall partitioning. Cattán et al. reported substantial stemflow and strong concentration of rainfall around banana plants, while Charlier et al. incorporated vegetation-mediated rainfall partitioning into a plot-scale runoff model [16]. These studies provide an important conceptual foundation for large monocot crops in which broad leaves and funnel-shaped architecture redistribute rainfall toward the plant base.

Enset (*Ensete ventricosum*), locally known as Warke (mean “Gold”) or false banana, provides an especially interesting case. It is a perennial monocot cultivated extensively in the Ethiopian highlands and is an important food-security crop [17,18]. Mature plants possess large leaves, a substantial pseudostem formed by overlapping leaf sheaths, and an extensive root system [19]. These characteristics suggest that Enset may intercept, store, convey, and redistribute rainfall differently from conventional annual cropland. The combination of broad leaves and a central pseudostem provides a natural hydraulic pathway from canopy to soil.

Despite these characteristics, Enset has not been adequately represented as an explicit hydraulic component of catchment -scale rainfall-runoff models. Existing approaches generally represent vegetation through land-use classes, empirical runoff coefficients, or simplified interception terms [16]. Such representations may overlook the potentially important interaction between leaf geometry, midrib conveyance temporary storage, stemflow concentration, and local infiltration.

This study addresses this gap by developing a process-oriented Enset hydraulic framework within a hybrid ecohydrological modeling system. The framework separates the Enset pathway from the non-Enset catchment pathway. The Enset pathway explicitly represents canopy interception, leaf storage, midrib conveyance, plant-basin storage, stemflow concentration, and enhanced infiltration in the stem zone. The non-Enset pathway is represented using an AHP-based rainfall-loss formulation. The resulting direct runoff is area-weighted at the basin scale.

The central hypothesis is that Enset influences runoff not merely through a generic vegetation coefficient but through a sequence of interconnected hydraulic processes: interception, temporary storage, leaf conveyance, stemflow concentration, and localized infiltration.

2. Materials and Methods

2.1 Study Area

1 The study was conducted in the Holeta catchment of the Upper Awash River Basin in central Ethiopia. The
2 catchment is located in the Oromia Region and extends approximately between longitudes 38.0°–38.7°E
3 and latitudes 8.5°–9.3°N. The model catchments area is approximately 167.7 km². Elevation ranges from
4 1,800 to 2,600 m above sea level (m.a.s.l.), with a mean of approximately 2,060 m.

5 The climate is characterized by a unimodal rainfall regime, with the principal rainy season occurring during
6 June- September. Mean annual rainfall (precipitation) is approximately 1,050 mm (range: 780–1,340 mm)
7 although substantial interannual variability occurs. Mean annual temperature is approximately 16.8 °C
8 (range: 10–24 °C).

9 Cropland dominates the catchment, accounting for approximately 90.8% of the basin. Other land-cover
10 classes include trees, built-up areas, and bare ground. The dominant soil groups include hydrologic soil
11 groups B, C, and D, with Nitisols and Vertisols among the principal soil types. These soils have substantial
12 water-holding capacity but spatially variable infiltration characteristics.

13 The outlet is monitored at Holeta, where daily streamflow observations are available. The study focuses on
14 the 1999–2008 period for which the rainfall-runoff modeling dataset was prepared.

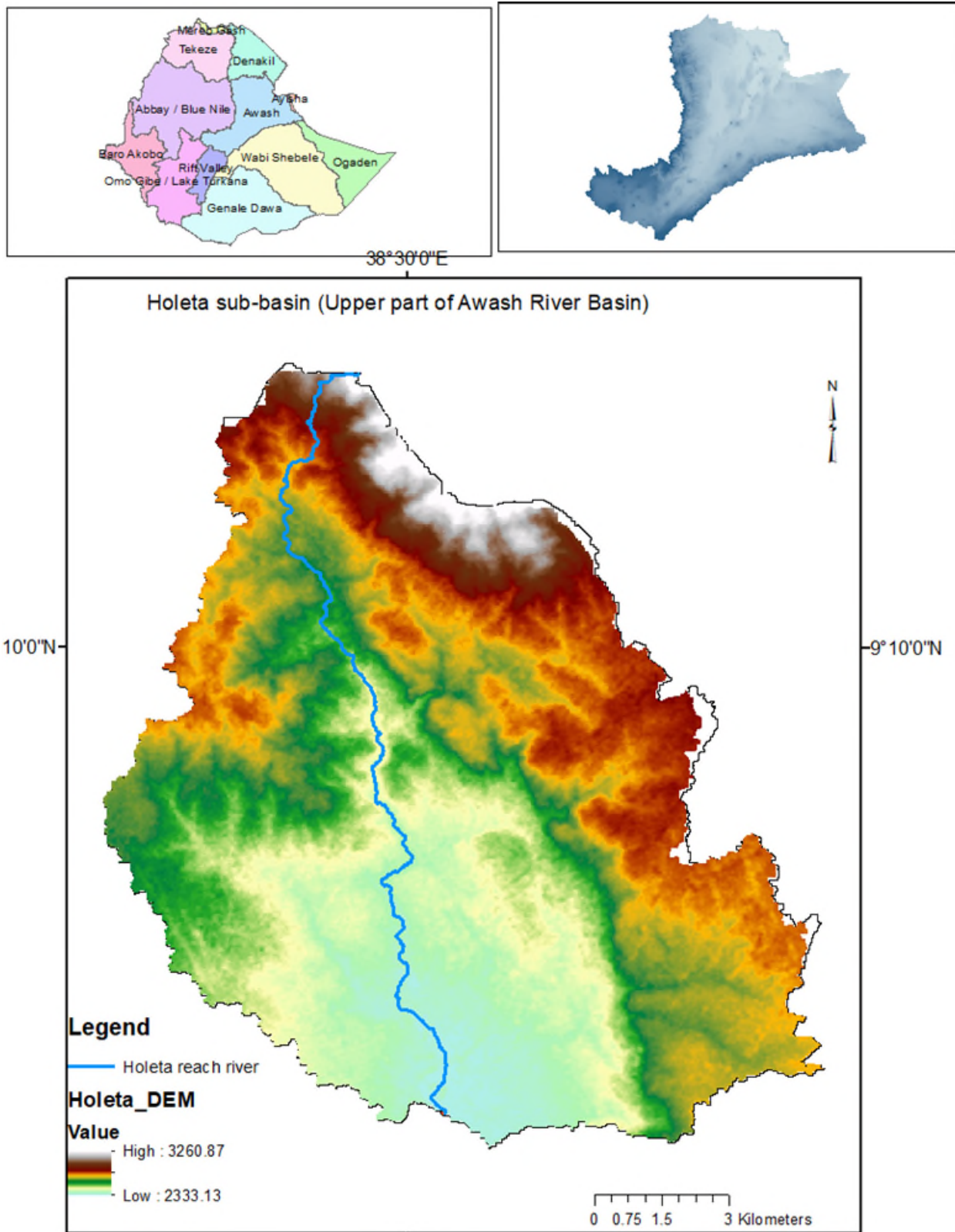


Figure 2-1: Study area and hydrological setting of the Holeta catchment in the Upper Awash River Basin, Ethiopia.

2.2 Hydrometeorological and spatial data

The modeling dataset comprised daily rainfall, temperature, streamflow, direct flow, baseflow, rainfall loss, and rainfall excess information. Rainfall observations were obtained from a network combining 15 gauges and CHIRPS virtual stations. Streamflow observations were obtained from the Holeta gauge.

Spatial information included land use/land cover, soil properties, and a digital elevation model. Land-cover information was derived from Landsat and Sentinel-2 imagery and field verification, while soil information was obtained from available FAO/ETHIOGIS datasets. A 30-m DEM was used for topographic analysis and catchment delineation.

The supplied land-use fractions were: cropland = 0.908; trees = 0.027; built-up area = 0.062; and bare ground = 0.003.

The Enset scenarios were defined relative to cropland rather than the entire catchment. Thus, the basin-wide Enset fractions corresponding to 0%, 15%, 30%, 50%, and 75% Enset replacement of cropland were 0%, 13.62%, 27.24%, 45.40%, and 68.10%, respectively.

2.3 Data preprocessing

Meteorological and hydrological records were subjected to quality control before modeling. The preprocessing workflow included temporal alignment, identification of missing observations, anomaly screening, outlier detection, and imputation.

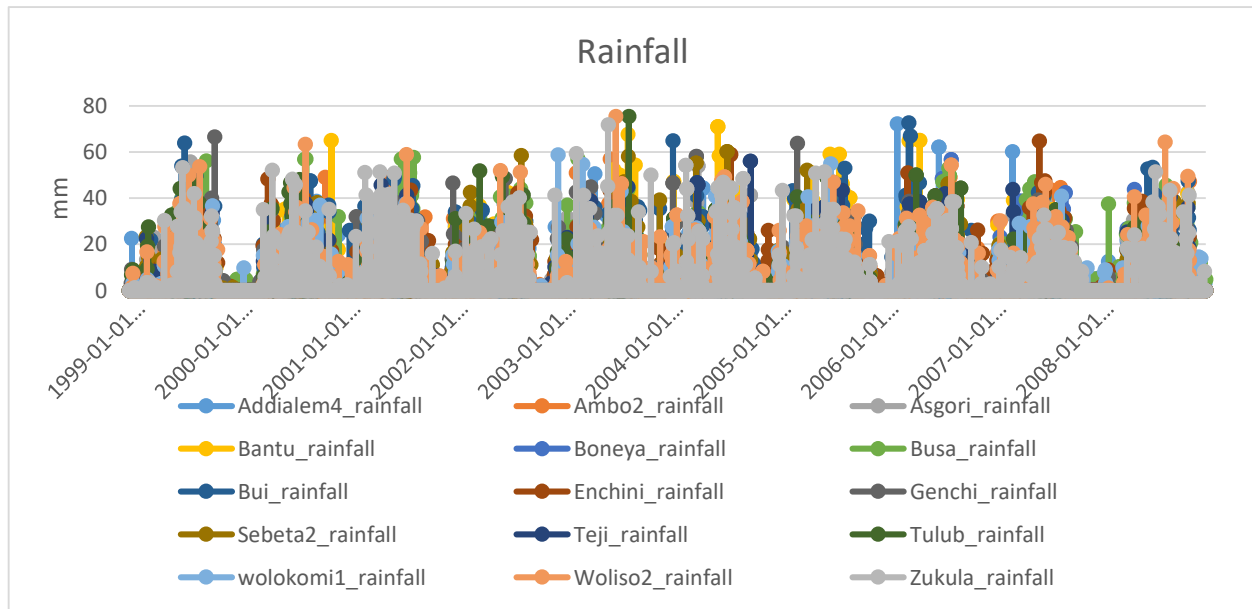
Values exceeding three standard deviations from the corresponding distribution were screened as potential outliers, while rainfall observations exceeding 300 mm day⁻¹ were flagged for additional inspection. Missing observations were addressed using Multiple Imputation by Chained Equations (MICE) with predictive mean matching. Five imputations and more than 20 iterations were used in the supplied preprocessing workflow.

The analysis assumes that the missing data were sufficiently close to missing-at-random conditions for imputation to provide reasonable estimates. The resulting daily time series were then converted

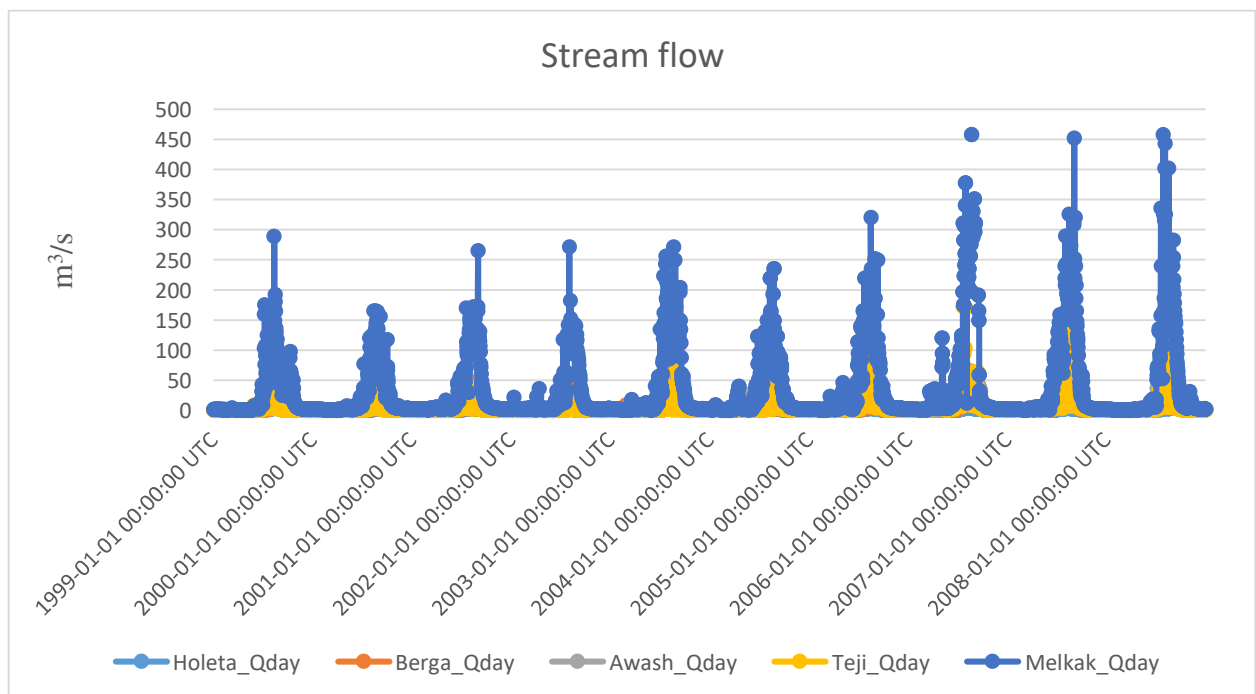
1 into model-compatible inputs

model-compatible

inputs



3 **Figure 2-2: Preprocessed rainfall dataset using R packages ([20])**



5 **Figure 2-3: Preprocessed flow dataset using R packages[20]**

2.4 Catchment delineation and spatial preprocessing

6

Catchment and sub-basin boundaries were derived using DEM-based terrain analysis and the HEC-HMS GIS workflow. Drainage networks, stream reaches, sub-basins, land cover, soil properties, slope, and other environmental attributes were linked to hydrological units.

The Holeta sub-basin was selected as the principal unit for implementation of the Enset ecohydrological process model. Spatial data were reclassified into hydrologically meaningful classes, and zonal statistics were used to estimate the area occupied by the relevant land-cover and soil categories

2.5 Analytic Hierarchy Process (AHP)- based representation of the non- Enset pathway.

The non-Enset portion of the catchment was represented using an Analytic Hierarchy Process (AHP). Five normalized criteria were used to characterize rainfall-loss processes: Infiltration capacity (I=40% weight) dominated the hierarchy, reflecting its critical role in reducing runoff through soil permeability and groundwater recharge. Morphometry (D=25% weight): Sub-basin shape, slope, and drainage density significantly influenced runoff velocity and peak discharge. Canopy interception (INT=8% weight): vegetation covers delayed runoff by storing rainfall on leaves and stems. Surface storage (S=15% weight): Topographic depression (quantified by TWI) temporarily retained water, reducing immediate runoff. Climate/Evaporation (E=12% weight)[20].

The composite loss index was therefore calculated as:

$$L = 0.4I + 0.25D + 0.15S + 0.12E + 0.08INT$$

where I, D, S, E, and INT are normalized catchment-scale indicators ranging from 0 to 1.

Because the available observations are catchment-scale, the AHP criteria are interpreted as normalized indices representing relative hydrological influence rather than direct measurements of plot-scale infiltration, storage, or evaporation.

A consistency ratio below 0.1 was used as the criterion for acceptable AHP consistency.

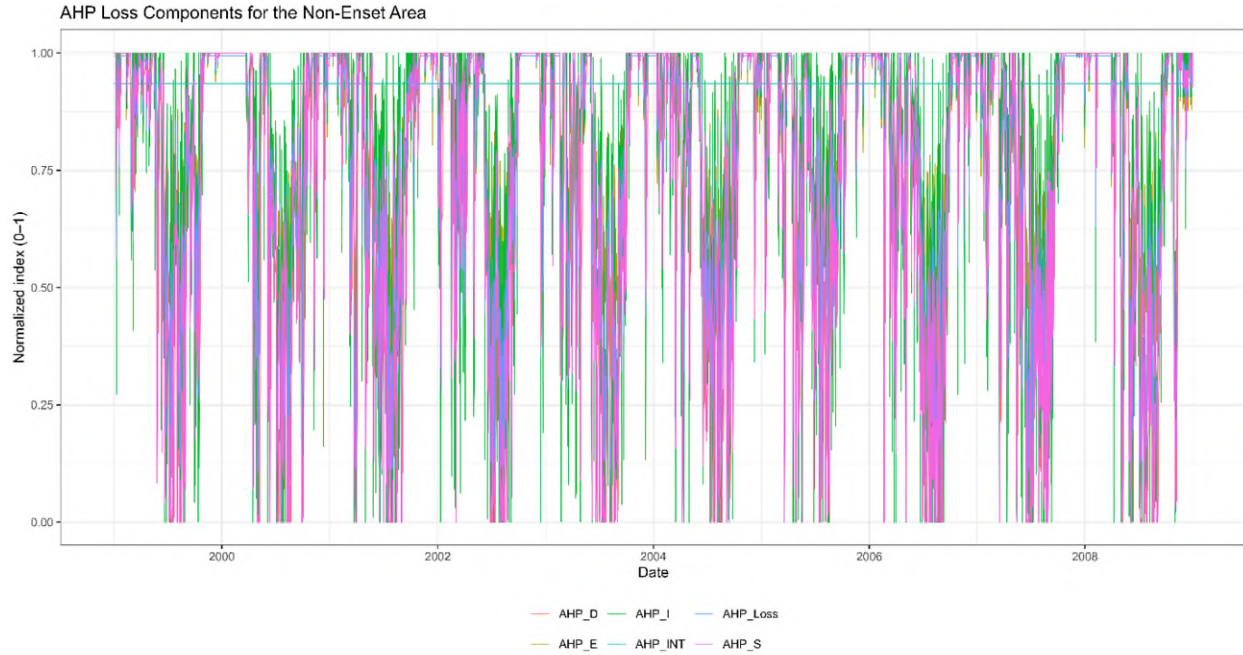


Figure 2-4: Temporal variation of the normalized AHP criteria and the resulting composite non-Enset loss index

2.6 Base flow separation and direct runoff

Observed streamflow was separated conceptually into a rapidly responding component and a delayed baseflow component. Where the supplied baseflow series was available, it was retained as the reference baseflow. Where baseflow was unavailable, recursive filtering was considered as a fallback approach.

Direct or quick flow was calculated as:

$$Q_{quick} = Q_{obs} - Q_{base}$$

where Q_{obs} is observed streamflow and Q_{base} is the baseflow component.

The supplied Direct flow series was retained as the preferred direct-runoff reference for model calibration and evaluation.

This distinction is important because the study specifically examines the influence of Enset on rainfall-generated direct runoff rather than attempting to attribute changes in groundwater-fed baseflow to vegetation intervention.

2.7 HEC-HMS rainfall-runoff framework

HEC-HMS was used to establish the hydrological representation of the catchment, including sub-basin delineation, rainfall-runoff transformation, loss estimation, and routing [21,22].

Environmental information derived through the AHP framework was used to inform rainfall-loss processes. Catchment response timing was represented through lag-time-based routing and the Clark unit hydrograph approach.

The HEC-HMS framework provided an independent hydrological benchmark against which the process-based Enset runoff formulation could be evaluated.

The modeling period was divided into:

- **Calibration:** 1999–2003;
- **Independent validation:** 2004–2008.

2.8 Process-based Enset hydraulic model

2.8.1 Enset Allometry

Normalized plant age t was used to represent development. Plant height follows the supplied logistic relationship:

$$H(t) = \frac{8.6}{1 + e^{-1.0(t-0.5)}}$$

where t is normalized age (0 to 1). Leaf length L (m) and width B (m) scale with height:

$$L = 4.64 \cdot (H/8.6)^{1.1}, B = 0.66 \cdot (H/8.6)^{1.0}$$

Leaf number increases from 8 to a mature configuration of 18 leaves in the principal implementation.

LAI= leaf Area Index, derived as.

$$LAI = P_g \times P_n \times L_A$$

P_g = plant per unit ground area coverage (plants/m²),

P_n =mean number leaf per plant

L_A = mean single-leaf area (m²) calculated via Turner's formula (1972a):

$$L_A = \sum (0.83 \times l \times b) / P_n$$

l = lamina length (m), b = maximum lamina width (m).

with $P_g = 5 \text{ m}^{-2}$.

2.8.2 Leaf interception and storage

The model treats the leaf as both an interception surface and a temporary hydraulic storage element. Leaf-film thickness is rainfall dependent and constrained to a finite range.

Total leaf storage was represented by:

$$V_{leaf} = \frac{2}{3}(0.83LB)t + (Lwt)$$

Where:

L = leaf length

B = maximum leaf width

t = water film thickness

w = midrib channel width

This formulation separates storage associated with the leaf lamina from storage associated with the midrib/channel.

2.8.3 Midrib hydraulic conveyance

The Enset midrib was represented as a semi-circular hydraulic channel. Its cross-sectional area and hydraulic radius were expressed as:

$$A = \frac{\pi w^2}{8}, R_h = \frac{w}{4}$$

Manning's equation was then used to estimate the hydraulic conveyance:

$$Q_{leaf} = \frac{1}{n} A R_h^{2/3} S^{1/2}$$

where (n) is Manning's roughness coefficient and (S) is the effective hydraulic slope.

The supplied model uses ($n=0.03$) and ($S=0.10$). A mature-leaf discharge of approximately 1.2 L s⁻¹ was treated as a hydraulic capacity benchmark rather than a continuously operating discharge

2.8.4 Radially distributed plant-basin storage

The plant basin was represented by a series of radial elements. For element (i):

$$V_b(i) = (1 - \psi_i)V_{b,tri} + \psi_i V_{b,cone}$$

$$\psi_i = \left(\frac{i}{N}\right)^2$$

Total basin storage:

$$V_{b,total} = \sum_{i=1}^N V_b(i).$$

Importantly, geometric storage capacity was distinguished from hydraulically active storage capacity. This distinction prevents the entire theoretical plant-basin volume from being interpreted as continuously water-filled.

2.8.5 Dynamic ring storage

Actual ring storage is a state variable bounded by the active storage capacity.

$$S_{ring}(t)$$

Where:

$$0 \leq S_{ring}(t) \leq V_{ring,max}.$$

The filling ratio becomes

$$F_{ring}(t) = \frac{S_{ring}(t)}{V_{ring,max}}$$

This is a physically meaningful quantity because it varies during rainfall.

The storage balance is

$$S_{ring}(t + \Delta t) = S_{ring}(t) + Q_{leaf}\Delta t + P_{direct} - Li - E - O$$

Where:

$Q_{leaf}\Delta t$ = inflow from the leaf,

P_{direct} = direct rainfall into the ring,

Li = Leakage(seep),

E = evaporation,

O = overflow.

The state is updated at each daily time step, permitting the hydraulic condition of the plant to change during rainfall sequences.

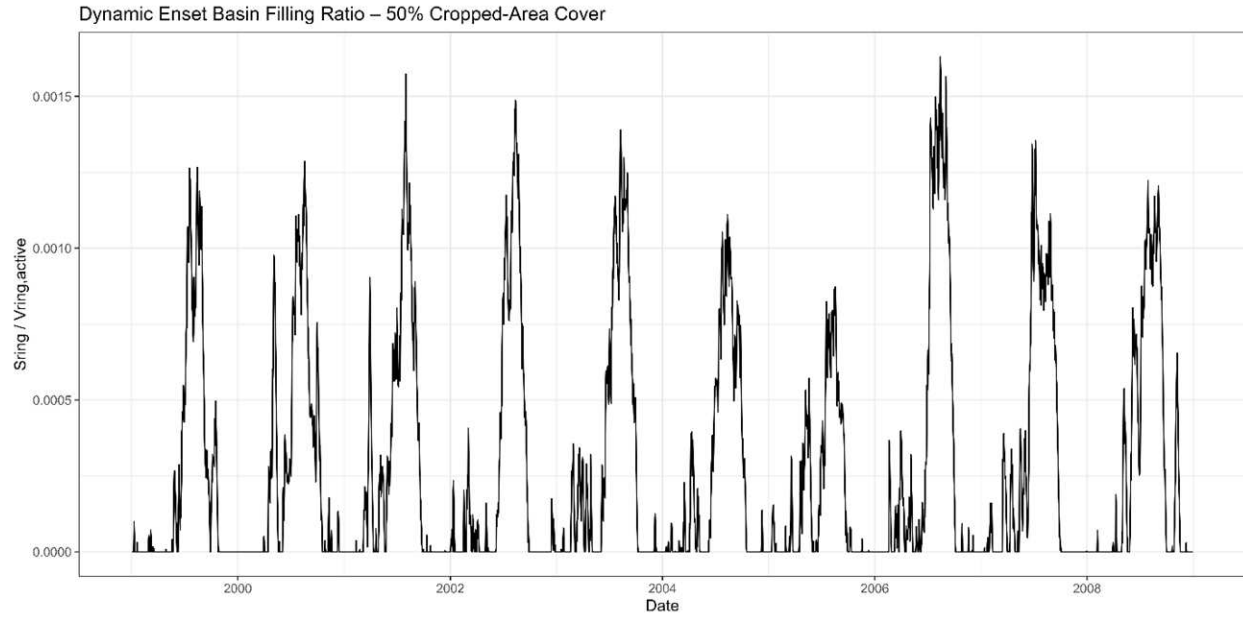


Figure 2-5: Dynamic Enset ring-filling ratio during representative rainfall events, illustrating the modeled activation and recession of temporary plant-basin storage.

2.8.6 Stemflow and stem-zone concentration

Stemflow is generated from hydraulic releases associated with the plant storage system and is constrained by available rainfall. A 0.5-m-radius stem zone is used to represent the area over which stemflow becomes concentrated. Local stem-zone loading is evaluated by dividing the stemflow depth by the stem-zone area fraction.

2.8.7 Stem-zone infiltration enhancement

The model incorporates the supplied 2.5-fold increase in saturated hydraulic conductivity within the stem zone due to root channels and organic matter. The basin-averaged effective capacity is:

$$K_{\text{eff}} = f_{\text{stem}} \cdot (2.5K_{\text{sat}}) + (1 - f_{\text{stem}}) \cdot K_{\text{sat}}$$

Stem-zone and non-stem-zone rainfall are evaluated separately before area-weighting their contributions to Enset direct runoff.

2.8.8 Direct-runoff generation

Runoff generation is based on the relationship between water-delivery intensity and infiltration capacity.

$$f_{stem} = \frac{A_{stem}}{A_{ground}}.$$

Stemflow is then concentrated onto that smaller area:

$$P_{sf,local} = \frac{P_{sf}}{f_{stem}}.$$

$$D_E = f_{stem} \max(0, P_{sf,local} - K_{eff}) + (1 - f_{stem}) \max(0, TF_{local} - K_{sat}).$$

where D_E is Enset-area direct runoff

The total Enset-area direct runoff therefore includes:

runoff generated by excess stemflow;

runoff generated by excess throughfall.

The final model can now explicitly test:

Enset cover $\rightarrow$ interception $\rightarrow$ leaf storage $\rightarrow$ midrib conveyance $\rightarrow$ ring storage
 $\rightarrow$ stemflow concentration $\rightarrow K_{eff} \rightarrow D_E \rightarrow D_{basin}$

while the remaining basin follows:

$$R \rightarrow L_{AHP} \rightarrow R_{eff} \rightarrow D_{NE}$$

$$L = 0.40I + 0.25D + 0.15S + 0.12E + 0.08INT$$

followed by:

$$R_{eff} = R(1 - L)$$

2.8.9 Basin-scale runoff aggregation

For an Enset fraction (C_E) of the cropped area, the basin-wide Enset fraction is:

$$f_E = C_E \times 0.908$$

The basin direct-runoff depth is then:

$$D_{basin} = f_E D_E + (1 - f_E) D_{NE}$$

where (D_{NE}) represents runoff from the remaining non-Enset area.

2.8.10 Calibration, validation, and performance metrics

Differential evolution (DEoptim) was used to calibrate hydrologically active parameters. The objective function combines NSE with penalties for high-flow mismatch and runoff-volume error.

Model performance was evaluated using NSE, KGE, R2, RMSE, PBIAS, and MAE. Calibration was performed from 1999 to 2003 and independent validation from 2004 to 2008.

2.3.1 Enset land-cover Scenarios

Five scenarios were evaluated:

Scenario	Enset cover of cropland	Enset fraction of whole basin
S0	0%	0.00%
S15	15%	13.62%
S30	30%	27.24%
S50	50%	45.40%
S75	75%	68.10%

The scenario design isolates the hydrological effect of progressively replacing cropland with Enset while keeping the representative mature-plant hydraulic parameters unchanged

3. Results

3.1 Model Calibration and independent validation

The 0% Enset baseline provided a useful reference for evaluating the rainfall-runoff framework.

During calibration from 1999–2003, the model produced NSE = 0.6522, KGE = 0.7576, (R^2) = 0.6552, RMSE = 2.138 m³ s⁻¹, PBIAS = 5.46%, and MAE = 0.938 m³ s⁻¹.

During independent validation from 2004–2008, the model produced NSE = 0.6105, KGE = 0.7176, (R^2) = 0.6156, RMSE = 2.362 m³ s⁻¹, PBIAS = 9.76%, and MAE = 1.004 m³ s⁻¹.

The decline in NSE between calibration and validation was 0.0416, while the decline in KGE was 0.0400. The relatively modest reduction suggests that the calibrated rainfall-runoff relationship retained useful temporal transferability. However, the increase in positive PBIAS indicates some deterioration in runoff-volume representation during the validation period.

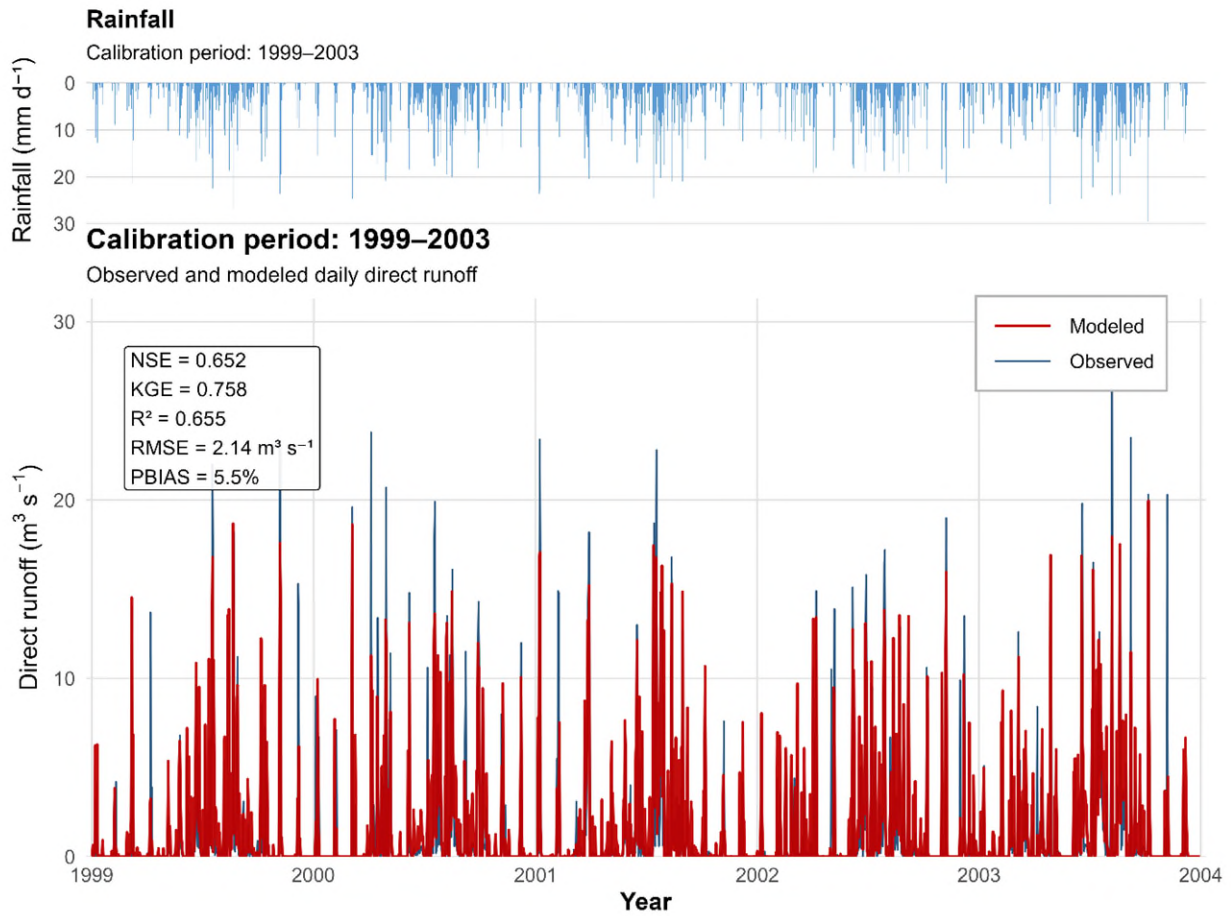


Figure 3-1: Calibration hydrograph

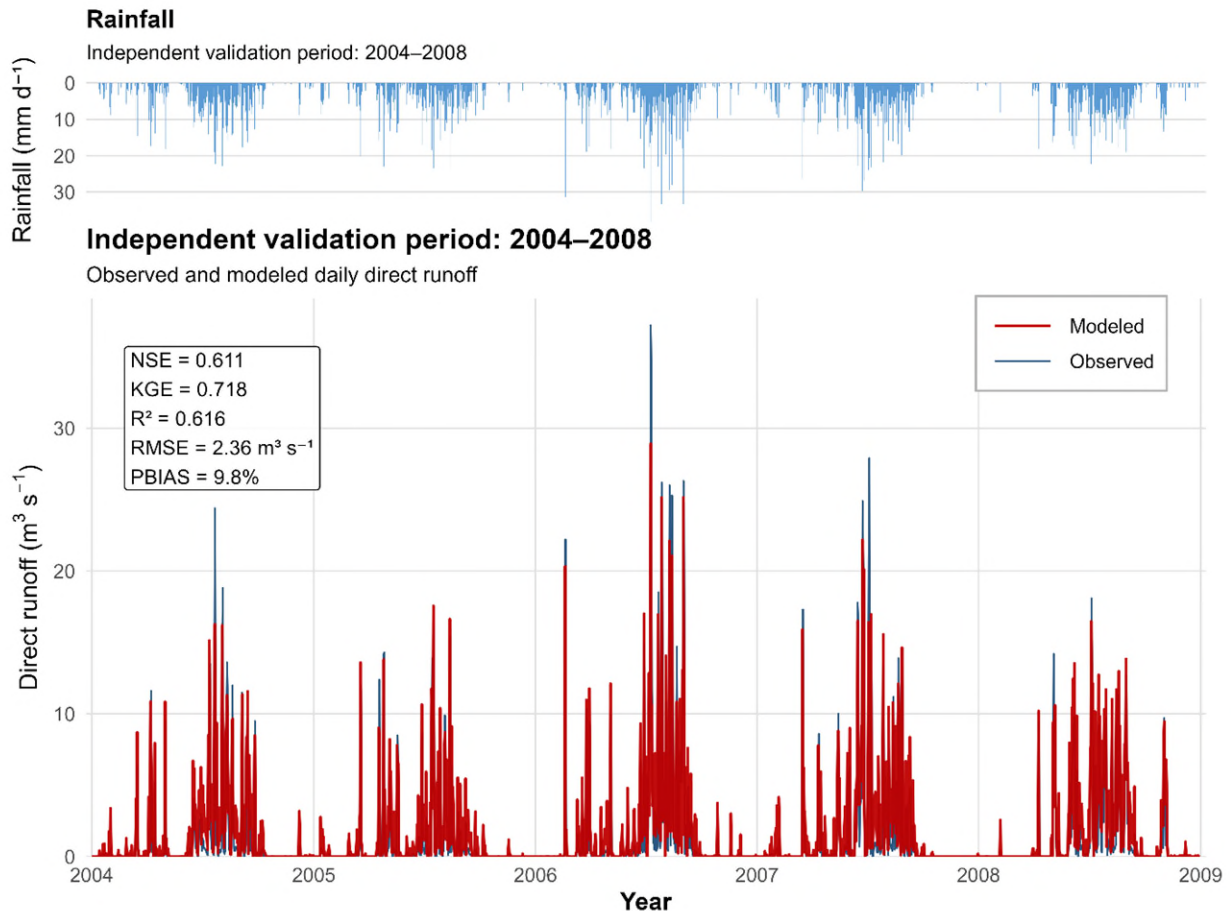


Figure 3-2: Validation hydrograph

3.2 Scenario response to increasing Enset cover

Increasing Enset cover produced a systematic decline in modeled direct runoff.

At 0% Enset cover, cumulative direct runoff was 2898.172 mm. This declined to:

2506.915 mm at 15%;

2115.657 mm at 30%;

1593.981 mm at 50%; and

941.886 mm at 75%.

Mean daily direct runoff declined correspondingly from 0.793368 to 0.257839 mm day⁻¹ across the scenario range.

The results therefore indicate a strong monotonic relationship between the proportion of cropland converted to Enset and modeled direct runoff.

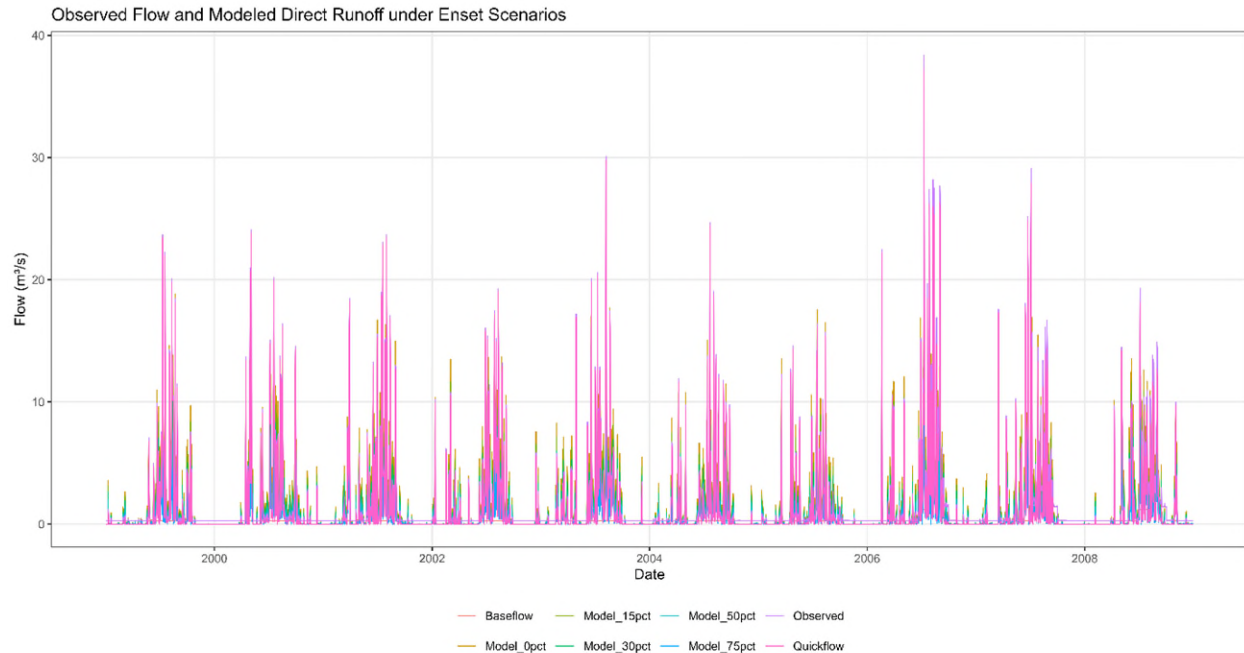


Figure 3-3: Modeled direct-runoff hydrographs under 0%, 15%, 30%, 50%, and 75% Enset cover of the cropped area.

3.3 Runoff and peak-flow reductions

Reduction in direct-runoff volume

Relative to the 0% Enset baseline, direct-runoff volume declined by:

13.50% at 15% Enset cover;

27.00% at 30%;

45.00% at 50%; and

67.50% at 75%.

The relationship is approximately proportional over the investigated scenario range, although the absolute hydrological response reflects both the expanding Enset area and the process-based difference between the Enset and non-Enset pathways.

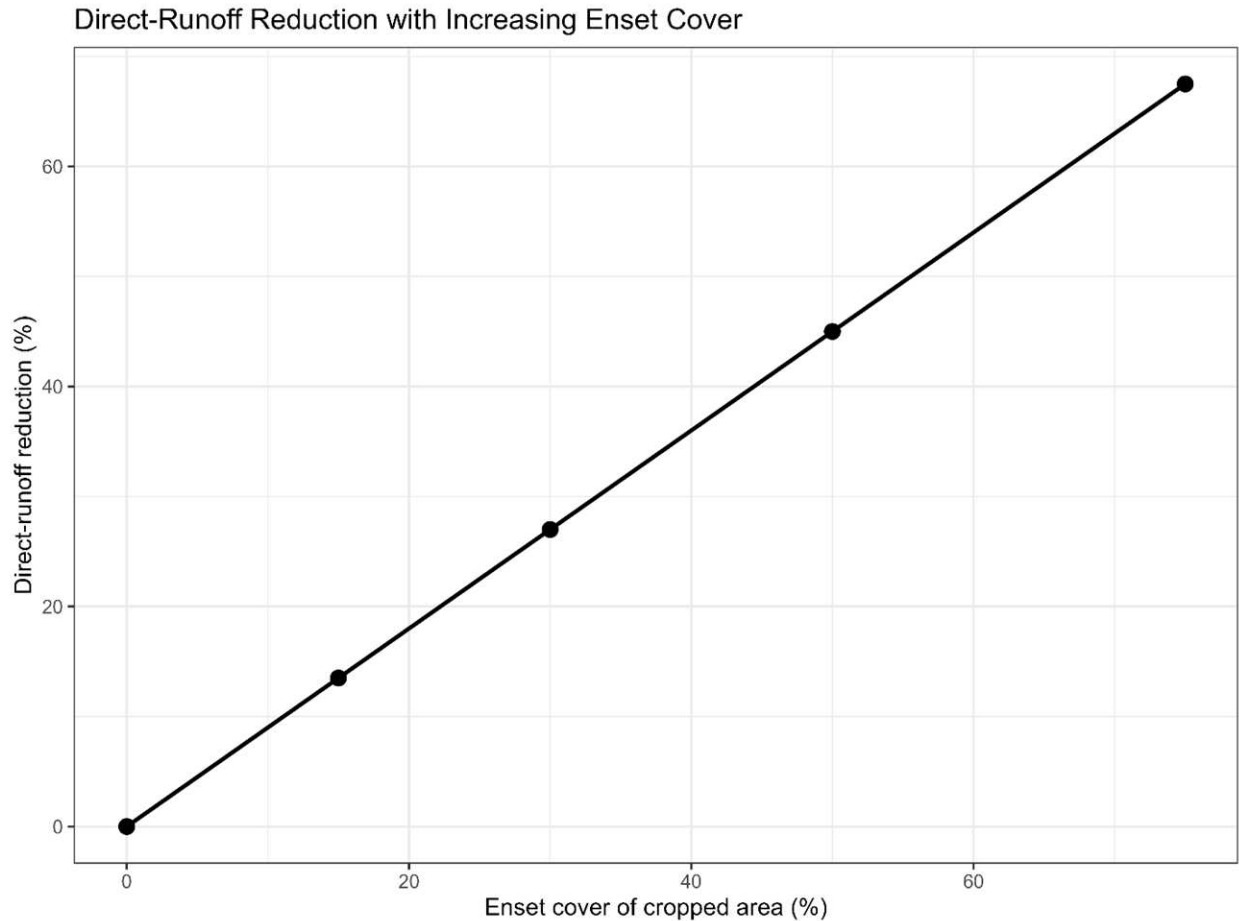


Figure 3-4: Reduction in cumulative direct runoff as a function of Enset cover of the cropped area. Points represent the five modeled scenarios, with the 0% scenario used as the reference condition.

3.4 High-flow response

The Q95 direct-runoff metric declined from $8.430439 \text{ m}^3 \text{ s}^{-1}$ under the 0% scenario to:

$7.290627 \text{ m}^3 \text{ s}^{-1}$ at 15%;

$6.150815 \text{ m}^3 \text{ s}^{-1}$ at 30%;

$4.631065 \text{ m}^3 \text{ s}^{-1}$ at 50%; and

$2.731377 \text{ m}^3 \text{ s}^{-1}$ at 75%.

Relative to the baseline, the reductions were 13.52%, 27.04%, 45.07%, and 67.60%, respectively.

The close correspondence between reductions in cumulative runoff and Q95 runoff suggests that the modeled Enset intervention affects both overall direct-runoff production and the upper portion of the direct-runoff distribution.

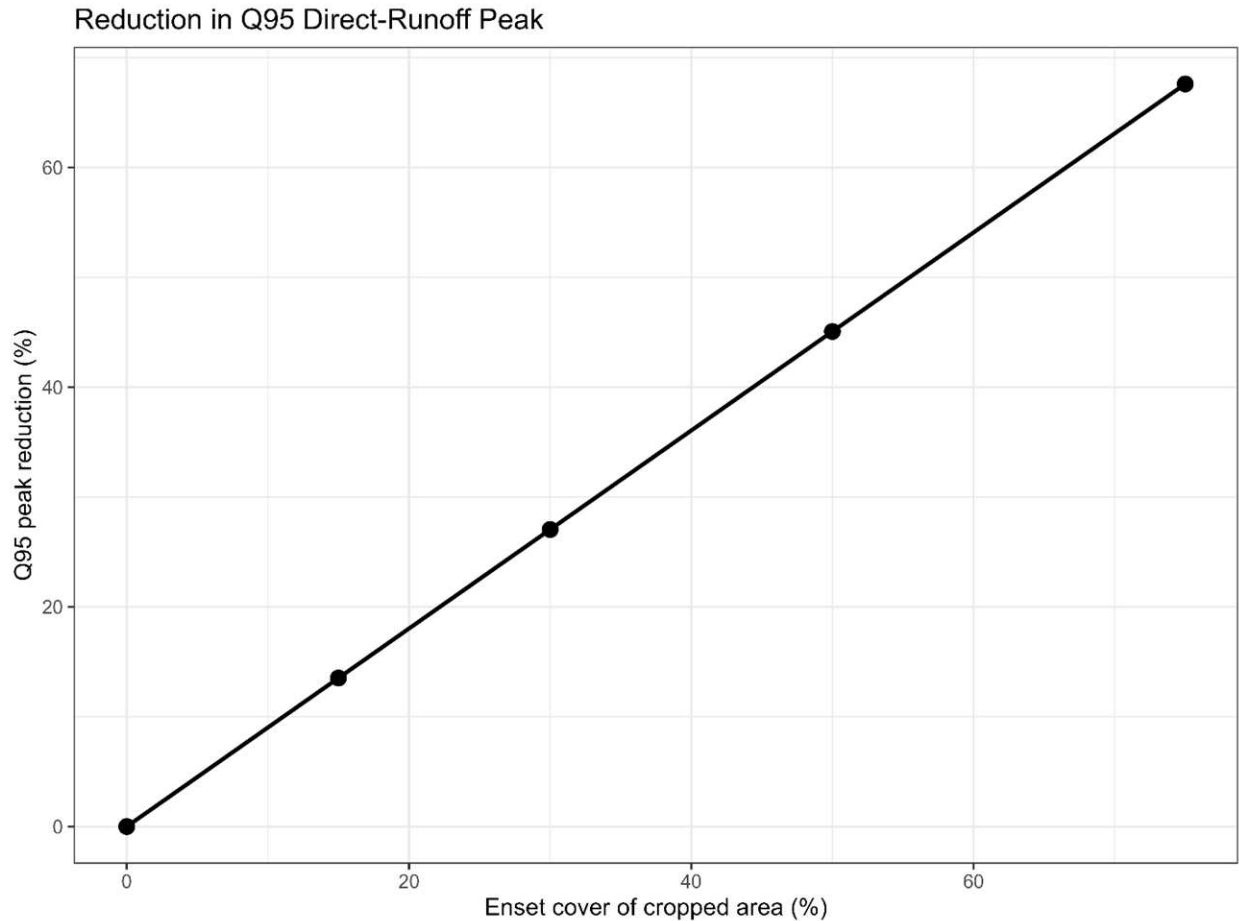


Figure 3-5: Reduction in Q95 direct-runoff discharge as a function of Enset cover of the cropped area.

3.5 Enset hydraulic indicators

The mean modeled stemflow was $0.037199 \text{ mm day}^{-1}$, corresponding to a mean stemflow-to-rainfall ratio of 0.005737.

Mean modeled interception was $0.827917 \text{ mm day}^{-1}$, while the mean effective hydraulic conductivity was $96.14419 \text{ mm day}^{-1}$ under the supplied parameterization.

The modeled ring-filling ratio was very small. The mean filling ratio was 0.000267, while its Q95 value was 0.001108. Thus, the dynamic storage component was only weakly activated relative to its theoretical active storage capacity during most of the simulation.

This result is important because it indicates that the modeled reduction in direct runoff should not be interpreted primarily as evidence of large volumes of persistent water storage in Enset plant basins. Rather, rainfall interception, redistribution, and enhanced infiltration appear to be more influential within the present parameterization.

3.6 Flow-duration response

The flow-duration analysis provides an integrated representation of how Enset cover modifies the distribution of direct runoff across the full range of simulated flows.

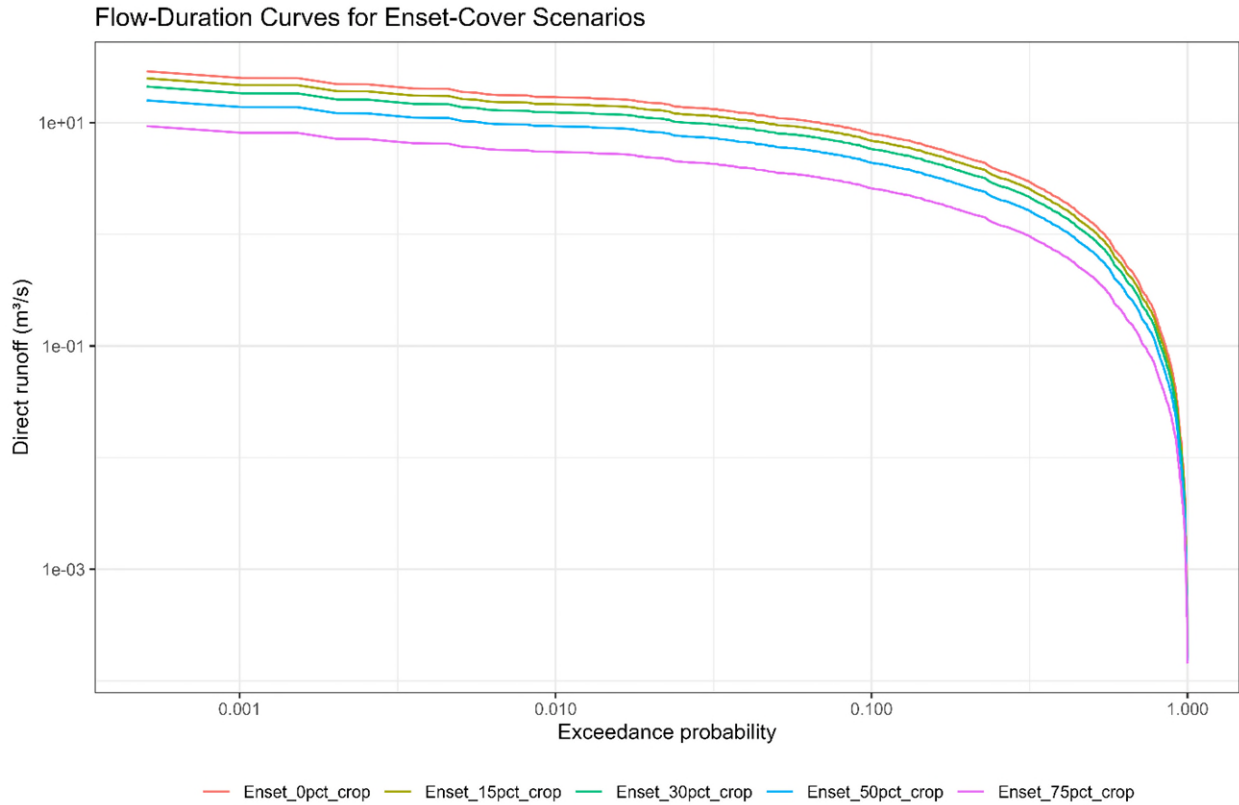


Figure 3-6: Flow-duration curves for the five Enset scenarios.

The progressive downward shift of the curves illustrates the modeled reduction in direct runoff across the flow distribution as Enset cover increases

4. Discussion

4.1 Enset acts as a hydraulic component rather than simply a vegetation class

The principal contribution of the proposed framework is conceptual as well as quantitative. Conventional rainfall-runoff models frequently represent vegetation through generalized land-cover parameters. Such representations can be useful at catchment scale but may obscure the mechanisms through which vegetation architecture modifies rainfall delivery.

The present model instead represents Enset as a hydraulic pathway. Rainfall is intercepted by large leaves, temporarily stored, conveyed through leaf midribs, redistributed toward the pseudostem, concentrated within a localized stem zone, and subsequently subjected to an infiltration threshold.

This sequence provides a more physically interpretable explanation for why increasing Enset cover reduces direct runoff under the model assumptions.

The resulting hydrological effect is therefore not simply attributable to “more vegetation.” It results from a specific sequence of rainfall partitioning and soil-water interactions.

4.2 Stemflow is redistribution, not runoff

An important interpretation of the model is that stemflow should not be equated directly with surface runoff.

Stemflow can increase the instantaneous hydraulic loading at the soil surface. If the resulting loading exceeds the local infiltration capacity, runoff can be generated. Conversely, if infiltration capacity is sufficiently high, the concentrated water can infiltrate without generating surface runoff.

The model therefore captures a competition between two processes:

concentration of water by the plant hydraulic system; and

enhanced infiltration in the receiving stem zone.

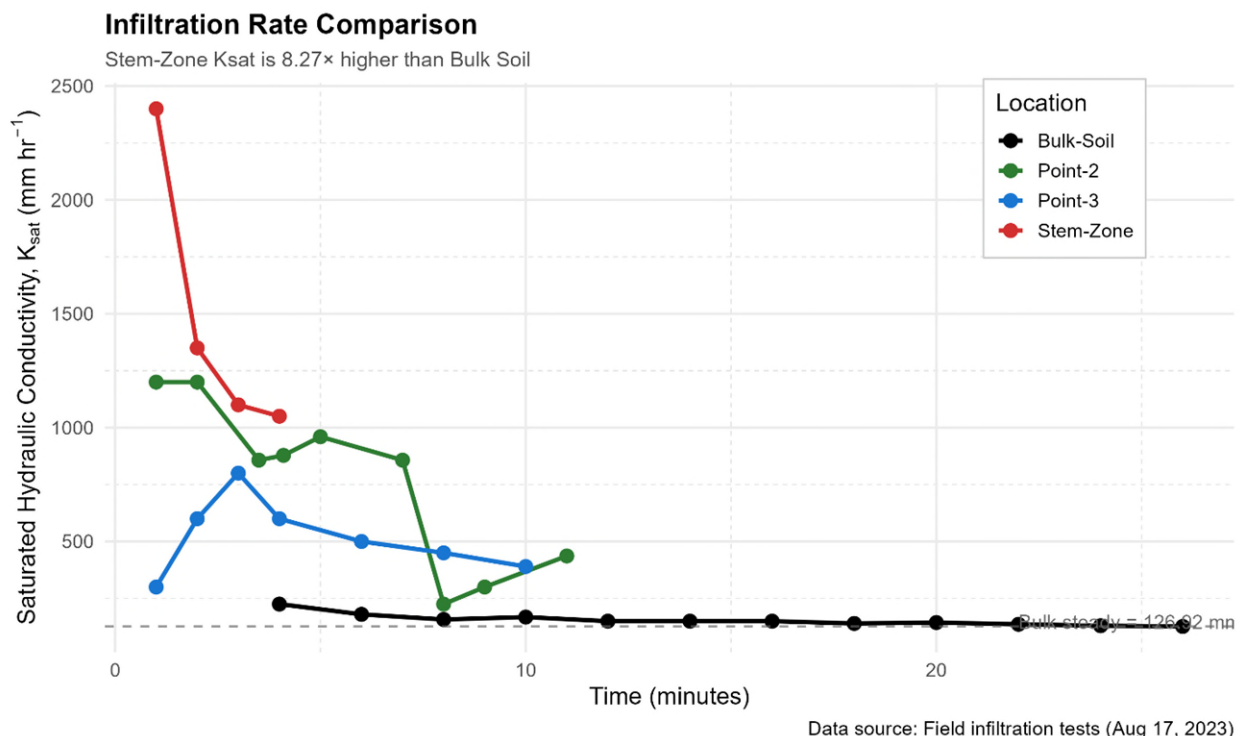


Figure 4-1: Field infiltration tests

The assumed minimum 2.5-fold increase in stem-zone saturated hydraulic conductivity strongly favors infiltration under moderate rainfall conditions. Under sufficiently intense rainfall, however, the concentration of water may exceed infiltration capacity, allowing runoff generation.

1 This mechanism provides a plausible explanation for why the hydrological effectiveness of
2 vegetation-based interventions is likely to depend on rainfall intensity rather than simply on
3 vegetation coverage.

4 4.3 Comparison with banana-based rainfall partitioning

5 Research on banana has established that large monocot canopies can generate substantial stemflow
6 and strongly redistribute rainfall. The Enset framework developed here builds on that conceptual
7 literature but moves toward a more explicit representation of plant geometry and hydraulic storage.
8 The similarities between Enset and banana—large leaves, overlapping canopy architecture, a
9 central pseudostem, and concentrated water delivery—make banana studies valuable analogues.
10 However, the results should not be interpreted as a direct transfer of banana stemflow
11 measurements to Enset.

12 The present study instead uses banana research as a conceptual and empirical benchmark while
13 representing Enset through its own allometric and hydraulic structure.

14 This distinction is particularly important because species-specific differences in leaf morphology,
15 midrib dimensions, canopy arrangement, soil conditions, and agricultural management can
16 substantially alter stemflow generation and infiltration.

17 4.4 Importance of crop-area scaling

18 An important methodological feature is the explicit distinction between Enset cover of cropland
19 and Enset cover of the entire basin.

20 Because cropland accounts for 90.8% of the basin, replacing 75% of cropland with Enset
21 corresponds to 68.1% of the entire catchment rather than 75%.

22 This distinction prevents overstatement of the spatial extent of the intervention and makes scenario
23 results more transparent.

24 It also provides a useful framework for comparing land-management scenarios across catchments
25 with different baseline land-cover compositions.

26 4.5 Dynamic storage is an important uncertainty

27 Although temporary storage is an important conceptual component of the Enset hydraulic system,
28 the modeled filling ratios were extremely low relative to the active storage capacity.

29 This finding requires careful interpretation.

1 It does not demonstrate that Enset has negligible storage capacity. Rather, it indicates that the
2 current parameterization and rainfall forcing rarely activate a substantial fraction of the modeled
3 storage capacity.

4 Consequently, the strongest uncertainty in this part of the model concerns the representation of:

- 5 • leaf water-film thickness;
- 6 • basin storage geometry;
- 7 • leakage;
- 8 • overflow;
- 9 • rainfall-dependent filling;
- 10 • evaporation; and
- 11 • the timescale over which stored water is released.

12 Field observations during natural rainfall are therefore required before the storage component can
13 be regarded as strongly validated.

14 4.6 Model performance and transferability

15 The baseline model produced NSE values of 0.652 during calibration and 0.611 during
16 independent validation. KGE values were 0.758 and 0.718, respectively.

17 The relatively small deterioration between periods suggests that the model retained useful
18 predictive behavior outside the calibration period. Nevertheless, the validation PBIAS of 9.76%
19 indicates that some systematic volume error remains.

20 The results therefore support the framework as a promising process representation rather than as a
21 fully validated operational flood forecasting model.

22 Further improvement should focus on field-constrained parameters and event-scale hydrological
23 processes rather than simply increasing model complexity.

24 4.7 Implications for nature-based flood management

25 The modeled scenario results indicate that Enset expansion can provide substantial reductions in
26 direct runoff under the investigated conditions.

27 At 30% Enset cover of cropland, modeled direct-runoff volume was reduced by approximately
28 27%. At 50%, the reduction reached approximately 45%, while the 75% scenario produced a
29 reduction of approximately 67.5%.

30 The corresponding Q95 reductions were nearly identical.

1 These results suggest that Enset could contribute to catchment-scale flood-risk management where
2 suitable land, soil, and climatic conditions exist.

3 However, these scenario results should be interpreted as **model-based potential**, not as directly
4 observed flood reductions. The scenarios assume representative mature Enset hydraulic
5 characteristics and therefore do not explicitly account for establishment-stage development, spatial
6 heterogeneity in planting density, differences among Enset landraces, or future changes in rainfall
7 intensity.

8 4.8 Enset should complement rather than replace conventional soil and water 9 conservation

10 The strongest management implication is not that Enset should replace conventional soil and water
11 conservation (SWC), but that it can potentially complement such measures.

12 Enset could be integrated with: contour bunds; terraces; grass strips; check dams; infiltration
13 structures; and other runoff-retention measures.

14 Such combinations may be particularly important during high-intensity rainfall when plant-
15 mediated infiltration alone may become insufficient.

16 The perennial nature of Enset also provides benefits beyond hydrological regulation, including
17 food production, soil organic-matter inputs, and potential contributions to landscape resilience.

18 4.9 Relevance under climate variability

19 The present analysis uses a historical climatic baseline and does not explicitly simulate future
20 climate scenarios.

21 This limitation is important because changes in rainfall intensity could alter the balance between
22 infiltration and runoff. An intervention that performs well under moderate rainfall may become
23 less effective when rainfall intensity exceeds both the soil infiltration capacity and the hydraulic
24 capacity of the plant storage system.

25 Future analysis should therefore combine Enset land-cover scenarios with climate projections to
26 determine whether the modeled runoff reductions remain robust under changing rainfall intensity
27 and seasonality.

28 A coupled climate–land-use framework would allow the intervention to be evaluated under
29 alternative climate trajectories rather than under a stationary historical climate alone.

4.10 Limitations and Uncertainty

Several limitations should be recognized when interpreting the results.

4.10.1 Limited field validation

The Enset hydraulic parameters were informed by morphology from 30 mature plants. This provides a useful initial basis but does not capture the full range of Enset landrace, age, management, and environmental variability.

4.10.2 Mature-plant assumption

The model primarily represents mature Enset. During establishment, leaf area, interception capacity, stemflow generation, and root development are lower. Consequently, scenario benefits may be smaller during the first years following planting.

4.10.3 Lumped catchment representation

The current model uses a catchment-scale area-weighting approach. It cannot fully resolve the spatial arrangement of Enset relative to drainage pathways, slopes, soil units, or flood-prone areas. A distributed implementation would allow optimization of planting locations rather than treating all Enset-covered areas as hydrologically equivalent.

4.10.4 Storage uncertainty

The low modeled ring-filling ratios indicate that the temporary-storage component remains weakly constrained. Direct measurements of filling, leakage, and overflow are required.

4.10.5 Climate non-stationarity

Future rainfall intensification was not represented. Consequently, the reported scenario reductions should not be interpreted as future-climate projections.

4.10.6 Interpretation of modeled scenario reductions

The large reductions under high Enset-cover scenarios are model outputs and should not be interpreted as directly measured catchment flood reductions. Independent field observations are required to establish the magnitude of the real-world response.

4.11 Implications for Catchment Management

The results support a strategic rather than blanket approach to Enset expansion.

Moderate levels of Enset integration may provide meaningful hydrological benefits while retaining substantial cropland for other agricultural purposes. The 30–50% cropped-area scenarios are particularly relevant because they produced modeled direct-runoff reductions of approximately 27–45%.

However, implementation should consider: soil infiltration capacity; slope; existing erosion-control structures; drainage-network connectivity; flood-prone areas; local farmer preferences; food-security requirements; and Enset establishment time.

Enset should therefore be considered one component of integrated catchment management rather than a stand-alone flood-control measure.

5. Conclusions

This study developed a process-oriented ecohydrological framework for representing Enset (*Ensete ventricosum*) as a hydraulic component of catchment rainfall-runoff processes.

The framework explicitly represents canopy interception, leaf and midrib storage, hydraulic conveyance, plant-basin storage, stemflow redistribution, stem-zone concentration, and enhanced infiltration. The non-Enset catchment is represented using a prescribed AHP loss formulation, while Enset and non-Enset pathways are combined through area weighting.

The baseline 0% Enset model produced $NSE = 0.652$ during calibration and $NSE = 0.611$ during independent validation, with KGE values of 0.758 and 0.718, respectively. These results indicate useful predictive skill while also demonstrating remaining uncertainty in runoff-volume representation.

The scenario analysis showed a consistent reduction in modeled direct runoff as Enset cover increased. Relative to the 0% baseline, direct-runoff volume declined by 13.50%, 27.00%, 45.00%, and 67.50% for 15%, 30%, 50%, and 75% Enset cover of cropland, respectively. Q95 direct runoff declined by 13.52%, 27.04%, 45.07%, and 67.60% over the same scenario range.

The results support the hypothesis that Enset can influence catchment runoff through plant-mediated rainfall redistribution rather than merely through a generic vegetation coefficient. In particular, the combination of interception, stemflow concentration, and enhanced stem-zone infiltration provides a physically interpretable mechanism for reducing direct runoff.

At the same time, the very low modeled ring-filling ratios indicate that the temporary-storage component is not yet sufficiently constrained to support strong conclusions about persistent Enset water storage. This uncertainty highlights the need for targeted field observations of rainfall

interception, stemflow, leaf-film storage, midrib discharge, plant-basin filling, overflow, and stem-zone infiltration.

Overall, Enset represents a promising nature-based hydrological intervention for the Ethiopian highlands. Its greatest potential may lie in integration with existing soil and water conservation measures and in strategic placement within catchments where runoff generation and flood exposure are greatest.

Future research should:

1. validate the Enset hydraulic subsystem using event-scale field measurements;
2. quantify variability among Enset landraces and growth stages;
3. develop a spatially distributed Enset hydrological model;
4. integrate Enset scenarios with future climate projections;
5. investigate interactions between Enset and conventional SWC structures; and
6. evaluate the economic and ecosystem-service implications of Enset-based flood-risk management.

Data and Code Availability

The reproducible modeling package should include the processed hydrometeorological dataset, original input workbook, calibrated R scripts, model parameter files, scenario outputs, figure-generation scripts, and software-session information.

Reference variables supplied from observations—including Loss, Excess, Directflow, Qbase, and observed streamflow—should remain explicitly distinguishable from modeled variables to ensure reproducibility and prevent accidental circular validation.

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Conflict of Interest

The authors declare no conflict of interest.

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