Improving Catchment Yield and Low-Flow Estimation Using HEC-HMS: Application of Loss Methods in a Case Study in Gabon

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Abstract

This study was focussed on low flow modelling for the purpose of estimating catchment yield in a tropical rainforest setting in Gabon using HEC HMS. It compares the Deficit and Constant (D&C) and Soil Moisture Accounting (SMA) loss methods, calibrated with limited hydrometric data from a regional catchment. The SMA method performed best, capturing baseflow and interflow contribution and providing more reliable dry season simulations. Despite limited flow records and gaps in precipitation data, calibration produced yields of 38-56 L/s/km² which were slightly higher than anticipated for the size of the study catchments in this hydrological setting and cast some doubt around the historical flows records used in this study. The work supports sustainable water resource management for mining developments and highlights the need for expanded monitoring networks to improve long term hydrological assessment and planning.

Keywords: Hydrologic modelling, HEC-HMS, soil moisture accounting (SMA), gabon

Introduction

Mining is among the most water-dependent industrial sectors where water is required for mining activities, e.g. ore processing, dust suppression and workforce supply. For many sites dewatering and water treatment are also a critical issue which should be considered in (pre-)feasibility studies. On the other hand, inadequate water management can lead to production downtime and regulatory non-compliance. At the same time, mining can alter catchment hydrology and water quality through land clearing, water abstraction, diversion works, erosion and sediment mobilisation, and mine water discharges creating risks for downstream ecosystems, stakeholders and communities. For these reasons, robust estimates of catchment yield and dry-season water availability are a basis of mine planning, environmental impact assessment, and operational water balance design, particularly where licensing decisions and environmental flow protections depend on low-flow conditions (Younger and Wolkersdorfer, 2004).

These issues are especially critical in data-scarce regions where baseline hydrometric networks are limited and projects must progress with short-duration datasets. Under such conditions, uncertainty in low-flow estimates can be material to both engineering design (e.g., sizing of raw-water storages, process-water recycle systems, and dewatering capacities) and environmental commitments (e.g., maintaining dry-season flows or setting discharge limits).

In Gabon, mining is a central pillar of economic diversification and the sector is expected to expand beyond the long-established manganese industry to include new or reactivated projects in iron ore, gold and other commodities. This strategic pivot increases the need for credible, site-relevant water resources characterisation because many prospective mining areas coincide with densely forested catchments that support high biodiversity and provide water services to local communities. At project scale, developers must demonstrate that water abstractions and discharges can be managed within seasonal constraints, including extended dry periods when streamflow is sustained predominantly by subsurface storage. Yet, available streamflow data are sparse in many parts of Central Africa and often rely on regional or historical donor catchments, which can introduce uncertainty when transferred to a specific mine area (Kittel *et al.*, 2018; Bogning *et al.*, 2021).

Tropical rainforest hydrology further motivates careful selection of hydrological models and methods. In humid tropical forests, infiltration capacities are often high and storm runoff generation frequently involves a combination of saturation-excess mechanisms and rapid subsurface stormflow, while dry-season discharge persistence depends on the capacity of soils and shallow groundwater to store and gradually release water (Bonell, 2005). Consequently, modelling approaches used to inform mine water availability and catchment yield should be able to represent (i) quick response during high-intensity rainfall and (ii) delayed interflow and groundwater recession that controls low flows. Continuous rainfall–runoff simulation provides a useful framework because it enables explicit tracking of soil moisture storage, evapotranspiration losses, and recharge over long periods.

Hydrologic Engineering Center Hydrologic Modelling System (HEC-HMS) is widely used for both continuous and event-based simulation and offers multiple loss and baseflow methods suitable for screening-level to detailed applications. Among these, the Soil Moisture Accounting (SMA) method provides a multi-store representation (canopy, surface, soil profile, and groundwater layers) that is designed to simulate long-term water balance and recession behaviour (Bennett and Peters, 2000), whereas the Deficit and Constant (D&C) method offers a simpler conceptualisation of soil moisture deficit recovery and infiltration capacity that can be attractive when available data are limited. Comparative studies in different hydro-climatic settings indicate that SMA can better represent storage-driven runoff and recession dynamics where wet–dry contrasts are important (e.g. Halwatura and Najim, 2013; Mobarhan and Sangchini, 2021), but the additional parameterisation can also increase calibration uncertainty.

Against this backdrop of expanding mining interest and limited hydrometric coverage in Gabon, this paper evaluates and compares the performance of the SMA and D&C loss methods within HEC-HMS for catchment yield estimation, with particular emphasis on low-flow simulation that underpins dry-season water supply reliability and environmental flow protection in mine water studies.

Methodology and Study Catchments

The study applied continuous infiltration loss modules to support catchment yield estimation for regional catchments in Gabon. Catchments were delineated using available digital elevation models, and basin average precipitation and evapotranspiration inputs were derived from local gauge records supplemented by regional climate datasets.

The D&C approach represents catchment losses using a single soil layer characterised by an initial moisture deficit and a constant infiltration rate, combined with a canopy interception component. This method offers a relatively simple conceptualisation of rainfall losses and runoff generation and requires only a limited number of parameters, making it attractive for applications with short or incomplete hydrometric records (Figure1a).

In contrast, the SMA method provides a more physically based representation of hydrological processes by explicitly simulating canopy interception, surface storage, soil zone moisture, and multi layer groundwater flow. The SMA configuration applied in this study comprises ten parameters governing infiltration capacity, percolation, evapotranspiration losses, and groundwater recession from two subsurface storage zones (Figure 1b). This structure enables dynamic tracking of soil moisture and delayed subsurface drainage, which are critical controls on baseflow persistence and dry season runoff in tropical rainforest environments. Although the increased parameterisation introduces additional calibration complexity and non-uniqueness, the SMA method is expected to provide a more realistic representation of interflow

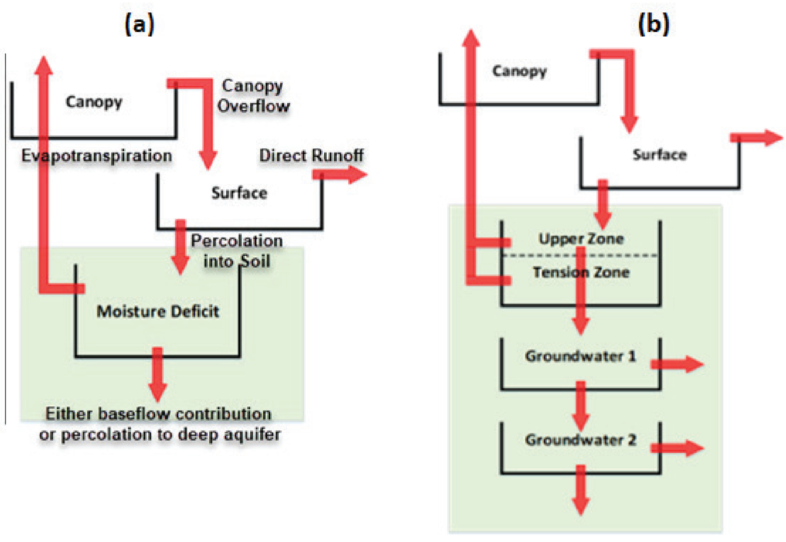


Figure 1 Model components of a) Deficit and Constant model b) Soil moisture accounting (HEC-HMS manual, 2013).

and groundwater contributions compared to simplified loss models.

Model performance was evaluated using a combination of graphical comparisons, cumulative flow analyses, and standard efficiency metrics. Particular emphasis was placed on assessing low flow simulation quality and flow recession characteristics, as these factors are most relevant for catchment yield estimation, abstraction licensing, and mine water supply reliability.

Both loss models were calibrated over a regional catchment with historical streamflow data records (ADHI 210). Figure 2 shows the distribution of the African Database of Hydrometric Indices (ADHI) hydrometry stations in Gabon. This paper presents the results for this regional hydro station in more detail.

The catchment upstream of ADHI 210 has an area of 117km2, with average annual precipitation of 1970mm and hydrometry data spanning the period 1967 to 1980.

Results and Discussion

Model parameters were calibrated and results for both loss methods are presented in Figure 3. Whilst both models have satisfactory performance, the SMA model outperforms the D&C method, especially in simulating baseflow. The performance criteria show a correlation coefficient of 0.78 and 0.85, and Nash-Sutcliffe efficiency (NSE) of 0.22 and 0.6 for D&C and SMA methods for the calibration period respectively. The SMA model performs better for baseflow and for much of the observed peak flows.

For low flows, the RMSE, correlation, logNSE and deviation from observed flow-duration-curve are 1.0, 0.48, -2.9 and -7.12% for the D&C method and 0.54, 0.6, 0.24 and -2.18% for the SMA method for the calibration period; and 1.4, 0.49, -7.3 and -52% for the D&C and 0.89, 0.36, -0.14. and -4.5% for SMA methods, respectively over the verification period. This shows the superior performance of the SMA method for low flow simulation compared to the D&C method.

Figure 3a shows SMA method slightly overestimates low flows and underestimate some historical high flows (Figure 3b) while the D&C method overestimates almost all high flows and underestimates low flow (Figure3a). Figure 4 shows the cumulative flow for observed and simulated results; the SMA model performance is much closer to the observed flow than the D&C model.

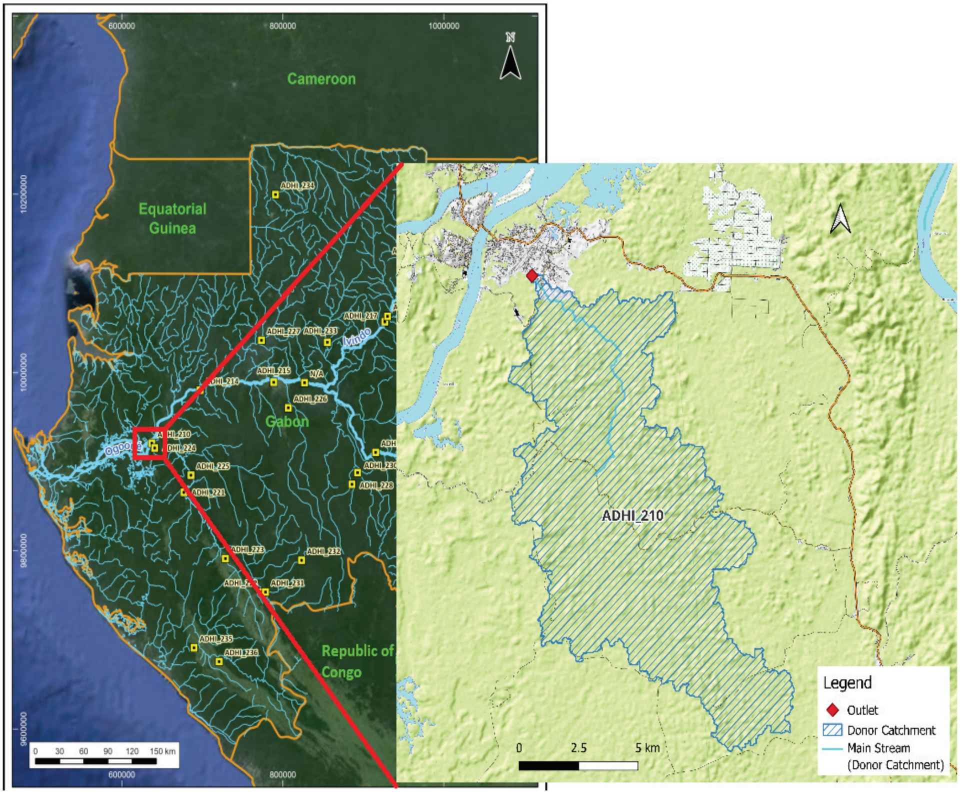
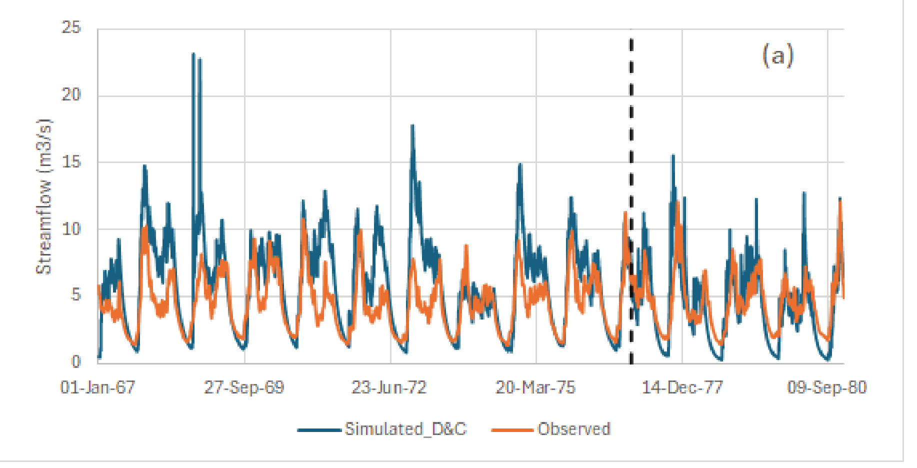


Figure 2 Location of ADHI in Gabon and ADHI 210 catchment.

Calibration results for the regional hydrometry station showed that there were major differences in the two methods ability to capture baseflow and dry-season runoff. The D&C method consistently underestimated late-season baseflows, resulting in abrupt reductions in simulated discharge. This behaviour is typical of simplified loss models that cannot track long-term soil storage or delayed subsurface drainage. SMA, by contrast, produced smoother recession curves, realistic groundwater contributions, and more stable low-flow representation.

The SMA approach better reproduced observed dry-season flows across ADHI-210 catchment based on performance metrics and visual goodness of fit of simulated to the observed, aligning with previous studies indicating that tropical rainforest catchments rely heavily on subsurface flow pathways and sustained soil moisture storage (Bonell, 2009). Normalised annual yield for SMA and D&C models are 37.9 and 55.6 L/s/km^2 respectively compared to an observed yield of 42.2 L/s/km^2, showing higher values compared with other regional hydrometric stations in Gabon and the Congo Basin.

It should be noted that quality assurance checks were performed on regional dataset to provide confidence in its reliability for model calibration. Table 1 indicates resulting runoff coefficient is relatively high (0.62) and evapotranspiration is likely underestimated (simulated average annual canopy evapotranspiration of 705 mm). Bruijnzeel (1990) presents actual annual evapotranspiration estimates for seven lowland tropical forest catchments in Central and West Africa which range from 1,145 mm/annum to 1,465 mm/annum with an average of 1,310 mm/annum. This indicates that the partitioning between evaporative losses and streamflow is not fully representative of expected catchment behaviour, with an excessive proportion of precipitation contributing to runoff. For similar tropical



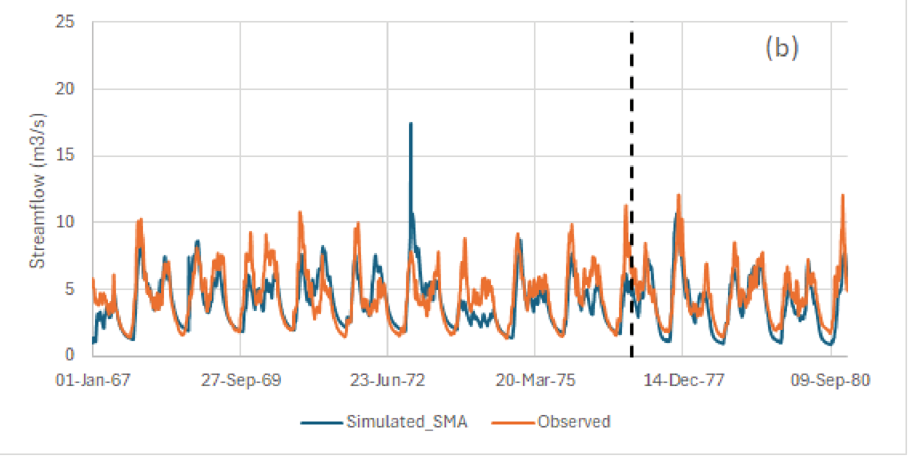


***Figure 3** Observed (black) vs simulated (blue) streamflow for a) Deficit and constant and b) SMA methods. Dashed line shows the start of verification period.*

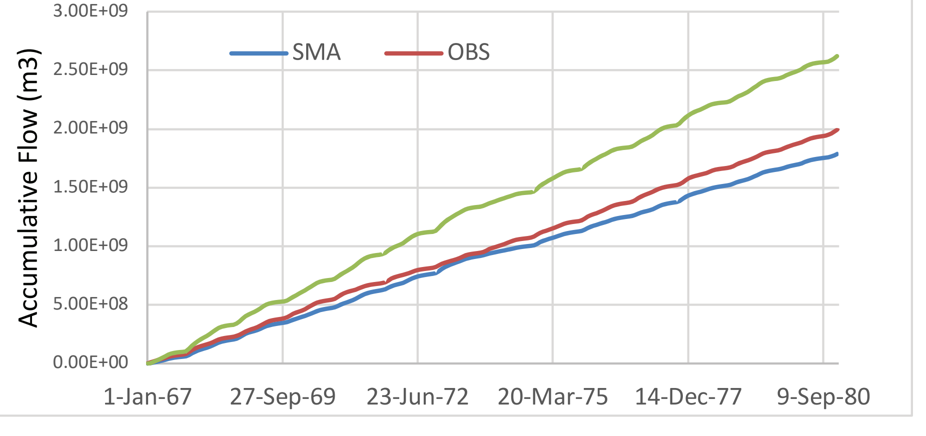


***Figure 4** Cumulative flows using Observed (red), and simulated flows (green line: Deficit and constant and blue line: SMA).*

regions, runoff coefficients of up to 0.6 and for Ogooe River at lower Ogooue, runoff coefficient of about 0.39 (Kittle *et al.*, 2018) have been reported, demonstrating the value of 0.62 lies at the upper bound of the reported range and should therefore be interpreted with caution. This finding also points towards a need for mines to establish their own local baseline monitoring network, with data quality assurance procedures established to ensure data captured is of sufficient quality, as regional historical datasets would appear to be less than ideal as potential donor catchments.

Conclusion

This study evaluated the performance of the Deficit and Constant (D&C) and Soil Moisture Accounting (SMA) loss methods within HEC HMS for continuous rainfall–runoff simulation and catchment yield estimation in a tropical rainforest catchment in Gabon, using calibration against a regional hydrometric dataset. The comparison focused specifically on the ability of each method to reproduce low flow behaviour and dry season streamflow, which are critical for water resource assessment and abstraction planning in mining contexts.

There are clear differences in the representation of baseflow and flow recession. The D&C method exhibited a tendency to underestimate late season flows, producing abrupt recessions that are inconsistent with the sustained dry season discharge observed in the regional record. This limitation reflects the simplified conceptual structure of the method, which does not explicitly account for long term soil moisture storage or delayed subsurface drainage. In contrast, the SMA method provided a more realistic simulation of interflow and groundwater contributions, resulting in smoother recession curves and improved low flow performance. This was reflected in stronger performance metrics for SMA method. The results are consistent with established understanding of tropical rainforest hydrology, where streamflow generation is strongly influenced by subsurface flow pathways and sustained soil moisture storage.

The relatively high runoff coefficient obtained from the regional catchment data assessment indicates that readily available regional historical streamflow records may not be suitable for local catchment yield analysis at mine development sites. While neglecting observed streamflow uncertainty can make calibration/evaluation conclusions inadequate, indicating a high performance metric (e.g. NSE) shows only that simulations are consistent with a plausible realisation of discharge. This issue highlights the need for expanded local monitoring networks to improve long term hydrological assessment and planning. Even a few spot flow measurements in wet/dry seasons can help to better evaluate the calibrated models

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Table 1 *Modelled catchment water balance for ADHI 210.*

Parameter	Depth (mm)	% Precipitation
Precipitation (during whole simulation period)	1934	100.0%
Canopy Evaporation (including root uptake from the soil zone)	705	36.4%
Rapid Runoff	1.7	0.1%
GW1 Out	659	34.1%
GW2 Out	543	28.1%
Deep Percolation	0	0.0%
Flow	1203	
Runoff Coefficient	0.62	

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