World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Groundwater recharge and geospatial heterogeneity by hydrological modelling under climatic influence: the case of the Davo River watershed (south-east of Côte d'Ivoire)

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World Journal of Advanced Research and Reviews, 2025, 28(01), 1857-1870

Publication history: Received on 12 September 2025; revised on 22 October 2025; accepted on 25 October 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.28.1.3587

Abstract

The sustainable management of groundwater resources in Côte d'Ivoire requires a reliable estimate of groundwater recharge. This study proposes a methodology for assessing the recharge of the Davo watershed (South-West Côte d'Ivoire) through distributed hydrological modelling with the HYDROTEL software. Physiographic (DEM, soils, land cover) and hydrometeorological (rainfall, discharge, evapotranspiration) data were integrated into the model via PHYSITEL. The three-layer vertical water budget (BV3C) was used to estimate vertical flows and potential aquifer recharge. The results indicate an average annual recharge of 221 mm, with spatial variability between –27 and 644 mm/year depending on the hydrological units. The performance of the model is considered satisfactory (Nash-Sutcliffe = 0.62), volume deviation = -1.11%). The sensitivity analysis shows the major role of evapotranspiration and land use on recharge, confirming the impact of deforestation and enthronization on the reduction of infiltration. This integrated approach provides a robust scientific basis for the quantitative assessment of groundwater resources and can be replicated in other similar contexts when all the required conditions are met.

Keywords: Recharge; Hydrological Modelling; Geospatial Heterogeneity; Davo River; Côte d'Ivoire

1. Introduction

Groundwater resources are now a major strategic issue for sustainable development. In Côte d'Ivoire, this issue has a critical dimension: the constant increase in groundwater withdrawals, combined with climatic uncertainties, requires rigorous and scientifically based management of groundwater bodies ([1], [2]). According to the National Guide for the Assessment of the Quantitative Status of Groundwater Bodies, the assessment of the quantitative status of these resources is based on a "Balance" test which compares the withdrawals made to the natural recharge of aquifers, thus determining whether a body of water is in "good status" or "bad status" ([3]).

This regulatory approach immediately raises a fundamental scientific question: how can we reliably estimate groundwater recharge? Historically, this issue has crystallized two distinct disciplinary approaches that have long evolved in parallel ([4]). On the one hand, surface hydrologists have developed models focused on the prediction of river flows, often considering groundwater flows as a loss for their study system. On the other hand, hydrogeologists have focused on groundwater dynamics, paying secondary attention to surface processes. This historical disciplinary

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dichotomy has gradually revealed its limitations, highlighting the need for an integrated approach to understanding the complexity of recharge processes.

Faced with the multiplicity of estimation methods available in the scientific literature, a rigorous methodological selection is necessary to identify the approaches best suited to the geographical and operational constraints of the Ivorian context. The selection criteria favour methods applicable to significant spatial units (several tens of km^2), capable of providing multi-year average estimates, allowing spatial aggregation from the scale of the catchment area to that of the water body, usable with limited parameters and easily accessible data, and finally economically viable for large-scale application.

The comparative analysis of the three main methodological families identified by ([5]): approaches based on flow balances, those using hydrograph analysis to determine baseflow, and those based on the analysis of piezometric fluctuations, reveals that distributed hydrological modelling is a particularly promising approach. According to these authors, surface water and unsaturated zone methods, such as surface hydrological models, estimate the potential recharge of water percolating from the surface layers to the water table, while those based on groundwater data generally provide estimates of actual recharge.

In this methodological context, the choice of the HYDROTEL software for the estimation of recharge is based on a convergence of scientific and technical arguments. As a distributed hydrological model, HYDROTEL meets the design requirements identified by [6] - system geometry, inputs, process formalization laws, initial state and boundary conditions, and outputs - while satisfying the stated selection criteria. According to [7], this distributed approach takes into account the spatial variability of hydrological processes, input variables and watershed characteristics. [8] identify two fundamental advantages of this approach: it can better capture spatial variability or heterogeneity and allows the consequences of scaling up to be studied.

The robustness of HYDROTEL has been demonstrated by its validation in various geographical contexts: initially validated on the Chaudière River in Quebec ([7], [9]), the model was then successfully tested in other Canadian provinces, in France on the Orb basin ([10]), in southern Quebec ([11]), and in Vietnam ([12]). Closer to our study area, HYDROTEL has proven itself in Côte d'Ivoire with successful applications in the N'zo ([1]), Bandama River ([13]) and N'zi ([4]) watersheds, demonstrating its adaptability to West African hydro-climatic conditions. Another decisive advantage is HYDROTEL's modular architecture and its capacity is particularly important for recharge estimation, as it allows the precise quantification of the different components of the water cycle ([14]).

The proposed methodological project thus constitutes a model for the quantitative assessment of groundwater resources, the approaches of which can be replicated in similar geographical contexts. The aim is to define the conditions for the success of a reliable estimate of recharge and to establish a reference methodological framework contributing to the sustainable management of Ivorian groundwater bodies.

2. Materials and methods

2.1. Study area

The Davo River is a tributary of the Cassandra River. It is located on the east side of this river which is located in the southwest of Côte d'Ivoire. The Davo River watershed covers an area of 7,194 km^2. It lies between longitudes 6°47 W and 5°69 W and latitudes 6°85 N and 5°03 N (Figure 1).

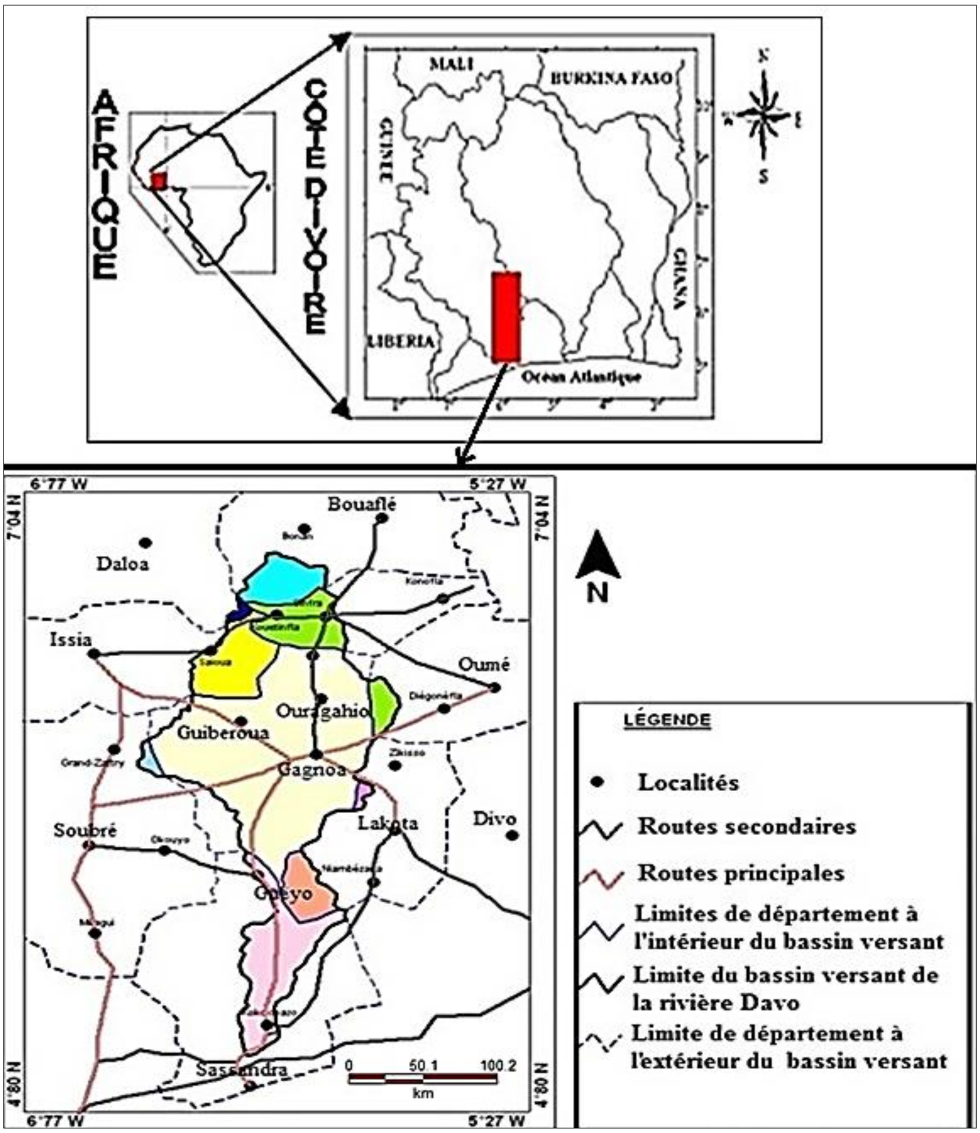


Figure 1 Geographic location and locations of the study area

With a total length of about 566.1 km, the Davo River crosses, from north to south, the various localities of Sinfra, Ouragahio, Guiberoua, Gagnoa, Gueyo, Dakpadou and Kokolopazo. This watershed has an elongated shape.

2.2. Materials

The hydrological modelling was conducted with the HYDROTEL system (INRS, Canada), including PHYSITEL 3.0 for the preparation of physiographic data (DEM, soils, land cover, hydrographic network) and HYDROTEL 2.6 for the distributed and continuous simulation of flows ([7], [9], [15]).

Input data included an SRTM DEM (90 m, NASA), daily rainfall series (1961-2016, 7 stations, SODEXAM), observed flows at 3 stations (ONEP), a soil map ([16]), as well as Landsat7 ETM+ (2000) and Landsat8 OLI/TIRS (2014) satellite images for land cover. Specific parameters (soil hydraulic properties, leaf area index, root depth) have been integrated into PHYSITEL.

Geospatial processing mobilized ENVI 4.3, MAPINFO 8.0/Vertical Mapper 3.0, ARCGIS 10.0, ERDAS, PCI and Google Earth. The coherence and stationarity of the hydroclimatic series were verified using KHRONOSTAT 1.01 (IRD) and the EVC programme ([17]). Together, this enabled reliable distributed modelling of the Davo basin and an integrated estimation of water recharge.

2.3. Methods

The estimation of aquifer recharge was achieved by the implementation of the distributed hydrological model HYDROTEL ([9]), specifically using the conceptual sub-model of the Three-Layer Vertical Balance (3LVB/BV3C). This approach allows for the annual and monthly hydrological balance of precipitation, surface runoff, actual evapotranspiration (REE) and potential aquifer recharge. The choice of this configuration is based on its prior validation in similar hydro-climatic contexts in West Africa ([1], [4], [13]).

The implementation of this approach first requires a phase, the constitution of the physiographic database, which involves:

- Preparation of input data;
- The spatial structuring of the watershed.

Then, a hydraulic parameterization phase that takes into account the hydraulic properties of the soils such as porosity, hydraulic conductivity, field capacity, wilting point.

Another phase follows the previous one and concerns the configuration of the HYDROTEL model. This is done through the choice of algorithms for calculating the model, which is based on feedback from previous studies in tropical environments ([1], [4], [9], [10]).

The algorithms selected for each sub-model are

- **Meteorological interpolation**: Weighted average of the three closest stations;
- **Potential evapotranspiration**: Hydro-Québec algorithm based solely on maximum and minimum temperatures;
- **Vertical water balance**: three-layer vertical balance (3LVB/BV3C);
- **Earth flow**: Kinematic wave;
- **River flow**: Kinematic wave.

At the BV3C sub-model, the soil is divided vertically into three functional layers ([9] Fortin et al., 1995):

- Layer 1 (10-20 cm): controls evaporation and surface runoff;
- Layer 2 (transition): manages delayed flows in the upper part of the soil;
- Layer 3 (deep): controls the base flow rate and recharge, kept close to saturation.

Soil discrimination makes it possible to obtain the variation in water content of each layer, which is modelled by continuity equations, taking into account vertical flows between layers, lateral flows and evapotranspiration losses. The flow Q_3 of the deep layer, assimilated to the potential recharge, is modeled as a function of the water content θ_3, the thickness of the layer and a recession coefficient kr.

Thus, a continuous simulation over 5 years (1991-1995) was carried out. It made it possible to:

- the establishment of the overall hydrological balance of the catchment area;
- the estimation of the spatial distribution of the potential recharge;
- the daily quantification of the balance sheet terms for each Relatively Homogeneous Hydrological Unit (RHHU/UHRH).

The potential recharge is directly provided by the $q_{2,3}$ flux of the BV3C submodel, representing the transfer of water from the intermediate layer to the deep layer, assimilated to the recharge of underground reservoirs. This integrated methodology allows for a spatially distributed and temporally continuous estimation of potential recharge, which is essential for the assessment of the quantitative status of groundwater bodies.

3. Results

3.1. Modelled physiographic characteristics of the Davo River watershed (DRW/BVRD)

The automatic delimitation (PHYSITEL) indicates an area of 6,943 km^2 for 857,161 pixels (90 m on each side), very close to the topographic reference (6,959 km^2), with a marginal underestimation of 0.23% leading to a faithful respect for the morphology of the basin (Figure 2).

The dominance of occupancy classes varies between UHRHs, generating differentiated responses in runoff, infiltration, evapotranspiration and interception. The overall hydrodynamics of the basin result from the aggregation of these elementary processes within the 223 UHRHs (Figure 3).

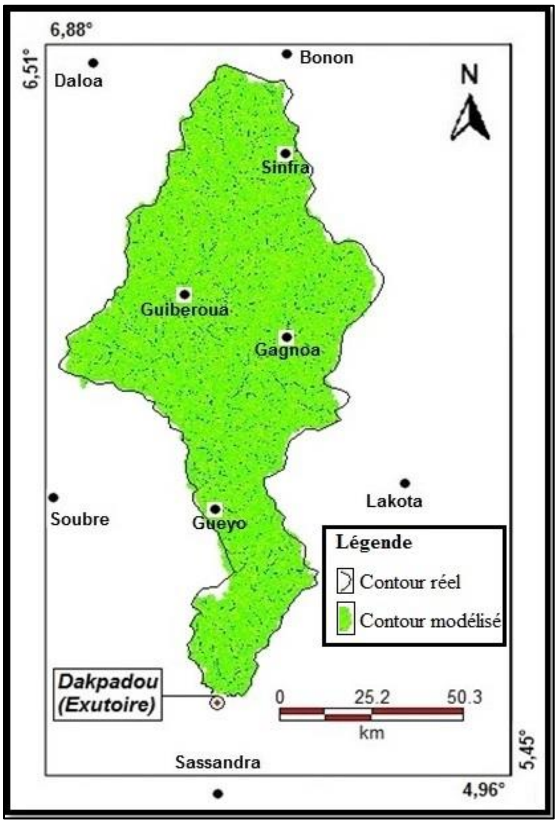
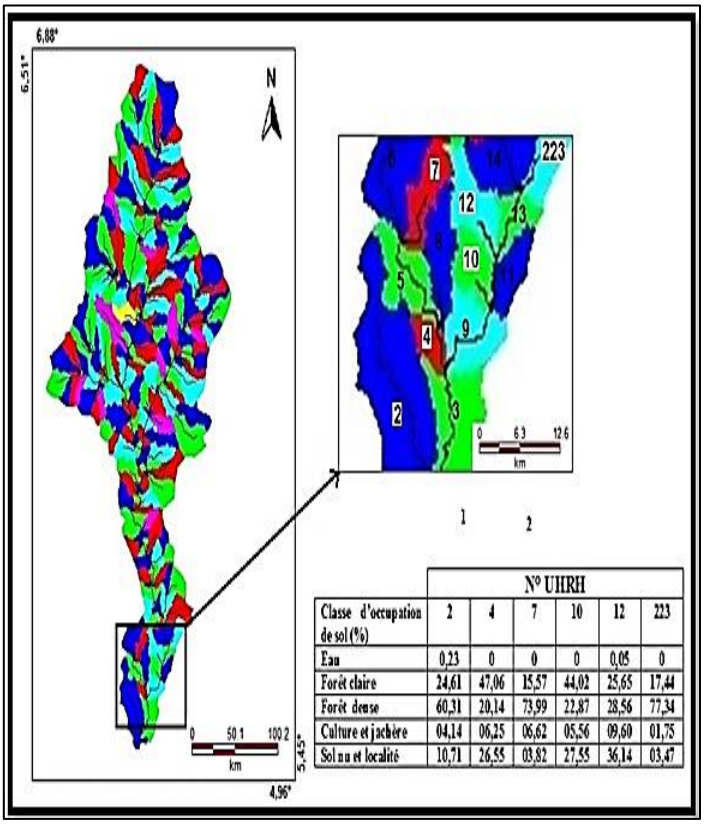


Figure 2 Actual contour of the basin (in dark black) imposed on the modeled contour



Classe d'occupation de sol (%)	N° UHRH 2	4	7	10	12	223
Eau	0,23	0	0	0	0,05	0
Forêt claire	24,61	47,06	15,57	44,02	25,65	17,44
Forêt dense	60,31	20,14	73,99	22,87	28,56	77,34
Culture et jachère	04,14	06,25	06,62	05,56	09,60	01,75
Sol nu et localité	10,71	26,55	03,82	27,55	36,14	03,47

Figure 3 Occurrence of land cover classes within each UHRH of the Davo basin

The hydrological model is based on three hierarchical sub-basins, defined according to the available hydrometric stations, resulting from the strategic grouping of the 223 UHRHs. This approach allowed a gradual calibration of the model, from upstream to downstream (Figure 4).

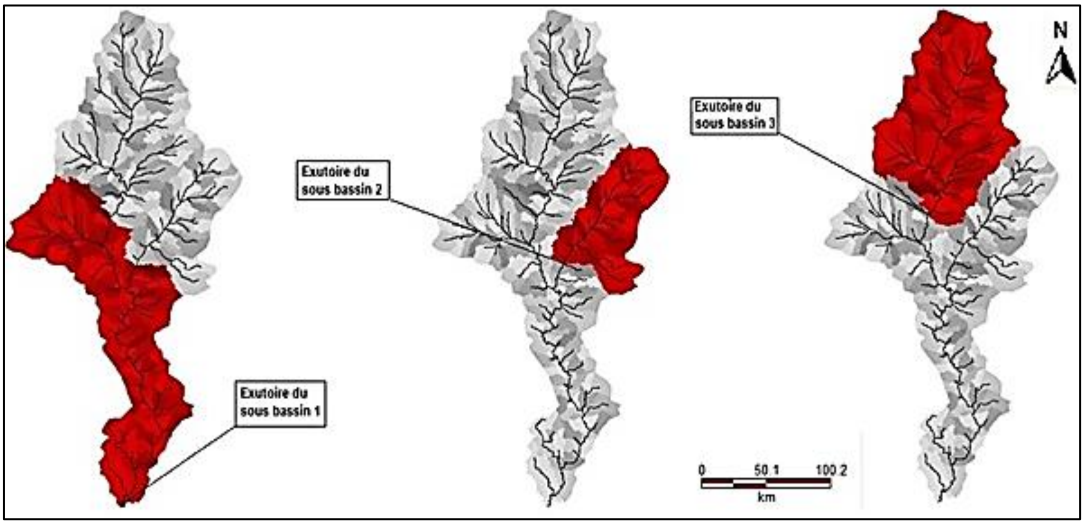


Figure 4 DRW model dunnage sub-basins

3.2. Performance of the HYDROTEL model

The evaluation of the performance of the HYDROTEL model (Figures 5 to 7) was carried out in three stages: calibration (1992-1993), validation (1994-1995) and simulation over the entire period (1991-1995).

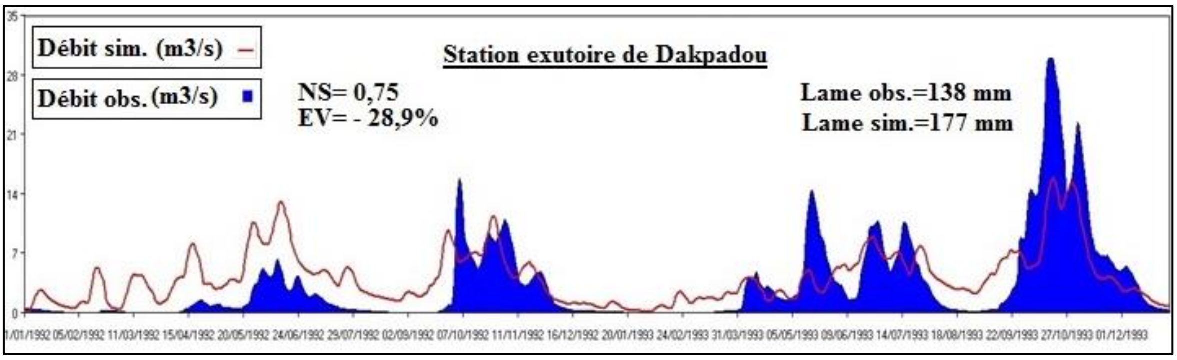


Figure 5 Hydrographs observed and simulated over the calibration period (1992-1993)

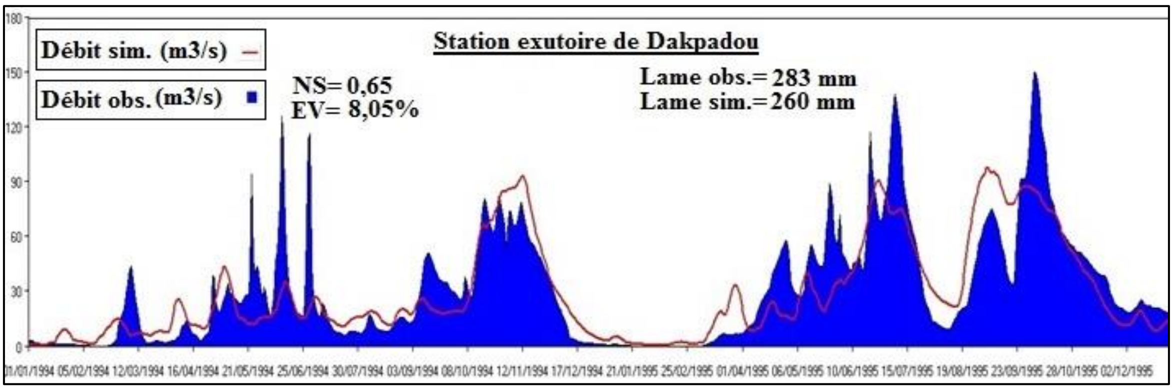


Figure 6 Hydrographs observed and simulated over the validation period (1994-1995)

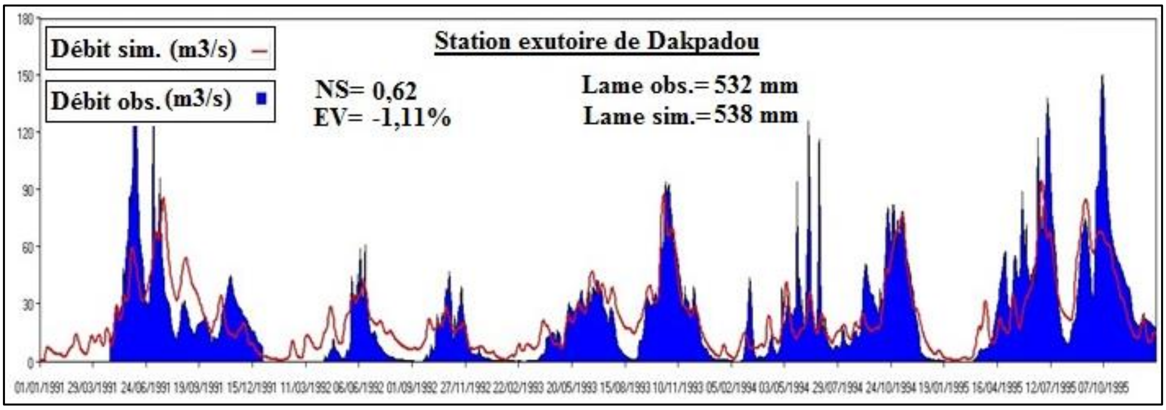


Figure 7 Hydrographs observed and simulated over the period of cross-simulation calibration/Validation (1991-1995)

The results show good model fidelity, with Nash-Sutcliffe (NS) coefficients generally above 0.60 and moderate volume deviations (VE) (Figure 8). Overall, the results indicate a good agreement between the simulated and observed flows, both for calibration and for validation and overall simulation.

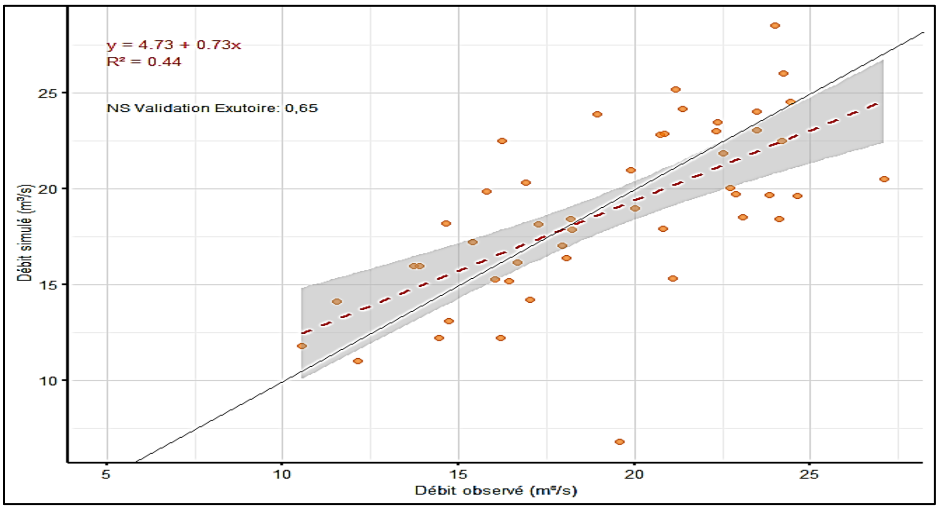


Figure 8 Relationship between observed and simulated flows

The quality of the models is *considered acceptable to good* by the stations to demonstrate the robustness of the model in representing the hydrological variability of the Davo River basin (Figure 9).

The scatter plot shows the correlation between the two series; The dashed line is the perfect fit (1:1), while the shaded area delineates the confidence interval associated with linear regression.

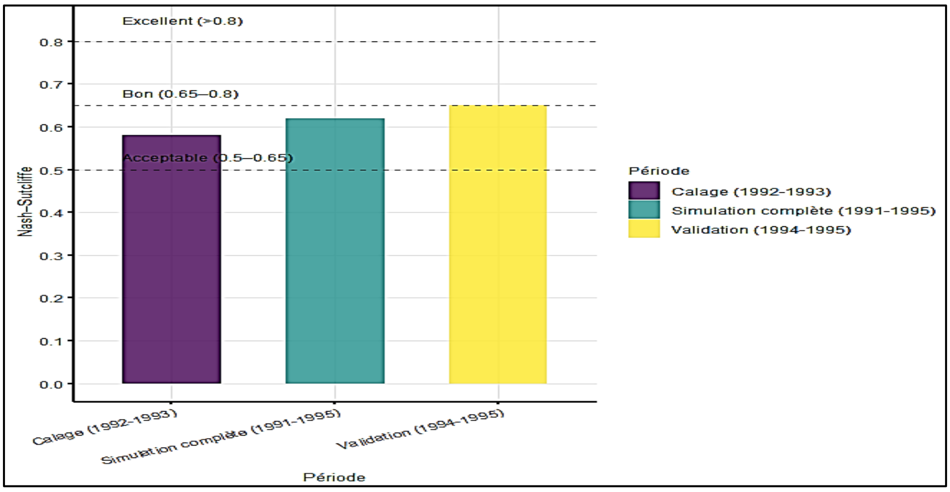


Figure 9 Performance of the HYDROTEL model by station in the Davo basin

3.3. Hydrological balance of the DRW (BVRD)

The results of the annual balance sheet recorded in Table I present the interannual variations in the elements of the water balance. Rainfall varies from 1328 mm (year 1991) to 991 mm (year 1992) with an average of 1193 mm/year. The average runoff is 40 mm/year, represents 3.39% of the rainfall and varies between 45 mm (year 1995) and 35 mm (year 1992), which leads to a flow deficit of 1153 mm/year, representing 96.61% of the rainfall, which will be distributed between the REE and the recharge of the underground reservoirs. The ETR varies from 1286 mm (year 1991) to 985 mm (year 1992), with an average of 1137 mm/year, i.e. 95.25% of rainfall. As for the values of the potential recharge of aquifers, they range from 282 mm (year 1995) to 167 mm (year 1991), with an average of 221 mm/year, which is equivalent to 18.52% of precipitation.

Table 1 Values of the annual components (mm) of the water balance based on the BV3C sub-model (1991-1995)

	1991	**1992**	**1993**	**1994**	**1995**	**Avg.**
Rain	1236	991	1187	1224	1328	1193
Flow	42	35	39	42	45	40
Flow deficit	1194	957	1148	1182	1283	1153
ETR	1286	985	1061	1175	1176	1137
Potential Charging	167	172	239	242	282	221

The results of the monthly report illustrated in Table II reflect the particularity of each month during the hydrological year in the Davo River watershed. Heavy rains occur over two periods; from March (139 mm) to June (149 mm) with a peak in May (184 mm) and then in October (152 mm). These heavy rains have led to waves flowing over these same periods varying from 4 mm (March and April) to 5 mm (June and October) through the peak of 6 mm (Month of May) on the catchment area. When the REE values are lower than those of rainfall, aquifer recharge begins in March (20 mm) and ends in October (47 mm) with an estimated peak in May of 67 mm. On the other hand, when the REE values are higher than the rainfall, it is found that the underground reservoirs support the baseflow of the hydrographic network. This translates into the negative values of the potential recharge that are observed from November to February.

From 1991-1995, the various results of the annual and monthly hydrological balance, obtained using the BV3C sub-model, show that the balance is in surplus over the entire Davo River watershed, with a recharge period of the underground reservoirs that extends from March to October. As HYDROTEL is a distributed model, it is possible to spatialize the overall results of the balance. Thus, a spatialized assessment of the potential recharge of aquifers made it possible to locate areas with high recharge rates for a more efficient management of groundwater resources.

Table 2 Monthly component values (mm) of the water balance based on the BV3C sub-model (1991-1995)

	Jan.	Feb.	March	Apr	May	June	Jul	August	Seven.	Oct.	Nov.	Dec.
Rain	10	61	139	145	184	145	71	85	97	152	63	33
Flow	0	2	4	4	6	5	2	2	3	5	2	1
Flow deficit	10	59	135	140	178	141	69	83	94	148	61	32
ETR	92	57	85	102	93	97	79	54	85	114	135	124
Potential Charging	-30	-1	20	33	57	47	10	21	22	47	-14	-16

3.4. Recharge estimation and uncertainties

The Monte Carlo simulation (Figure 10) made it possible to quantify the uncertainty associated with the estimation of recharge. The resulting distribution reveals a median of 140.8 mm/year, with a P5-P95 confidence interval of between 112 and 172.7 mm/year and a coefficient of variation of 13.4%, reflecting moderate variability.

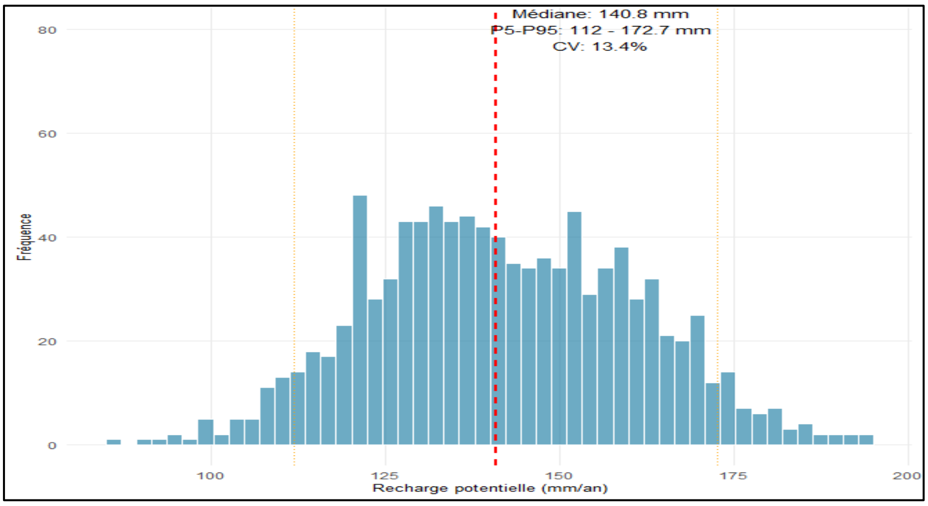


Figure 10 Distribution of uncertainty on potential recharge (Monte Carlo simulation)

3.5. Sensitivity of the Nash-Sutcliffe criterion to the evapotranspiration coefficient

The observation in Figure 11 highlights the importance of the parameterization of the evapotranspiration coefficient (ETP) in the performance of the model. The Nash-Sutcliffe criterion varies almost parabolicly according to this parameter, with an optimum around intermediate value (NS ≈ 0.62-0.65). This behaviour reflects the strong influence of atmospheric flows on the water balance, of which evapotranspiration is one of the major factors conditioning recharge.

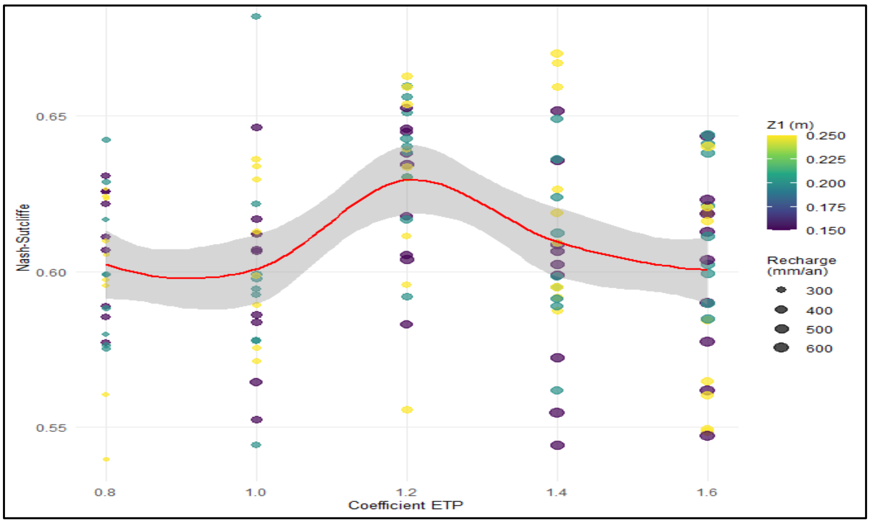


Figure 11 Sensitivity analysis of the parameters of the HYDROTEL model

Standardized sensitivity indices are represented for the main hydrological variables, grouped by parameter categories: ETP (evapotranspiration), Vertical (vertical water flows in the unsaturated zone of the soil) and Lateral (lateral flow).

3.6. Spatial distribution of potential recharge

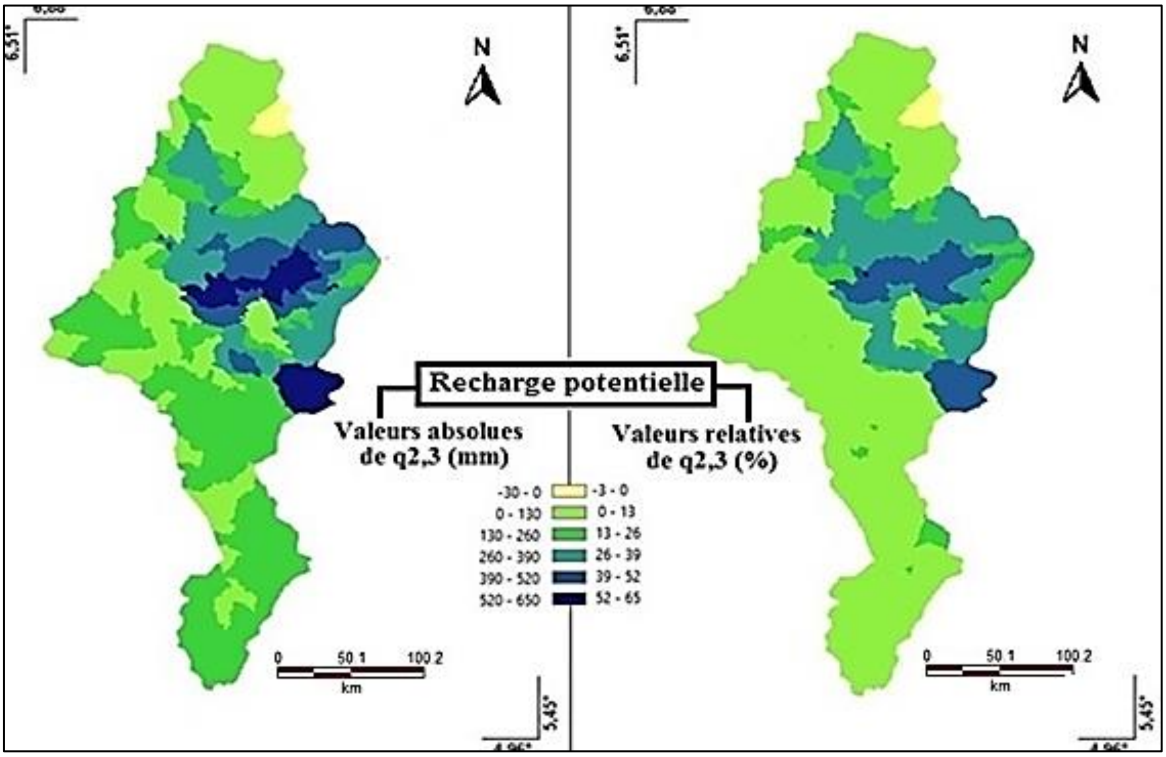


Figure 12 Spatial distribution of annual potential recharge a) absolute values of q2.3 and b) relative values of q2.3

The spatial distribution of potential recharge from the Davo River aquifer (Figures 12a and 12b) was based on the spatial division of the watershed into 223 UHRH. The potential recharge of the Davo River aquifer, estimated on 223 homogeneous hydro-distributed units (UHRHs) for the 19911995 period, shows high spatial variability. The absolute recharge values (q2.3), reflecting the intrinsic capacity of the soil to recharge, range from -27 to 644 mm/year (mean 221 mm/year), while the relative values (q2.3/rainfall), indicating the fraction of rain contributing to recharge, range from -2% to 54% (mean 18%). Six classes can be used to characterize this distribution: the areas with negative recharge (-30 to 0 mm/year, -3 to 0%) are located in the north-east (1.11% of the basin), the low recharge (0–130 mm/year) cover 30.13% of the basin, the intermediate recharge (130–260 mm/year) represents 38.74%, and the highest values

(260–650 mm/year, 30.2%) correspond to the Centre-East and Centre-North, identifying the sectors with maximum infiltration. Relative recharge is dominated by the 0–13% class, representing 62.67% of the basin, located in the north, east and south, highlighting the high spatial variability.

4. Discussion

4.1. Land use dynamics and soil properties

The integration of surface conditions into homogeneous hydro-distributed units (UHRH) has allowed a better structuring and description of hydrological processes. The geospatial data integrated into the PHYSITEL GIS has thus led to the design of a hydrological model for the Davo River watershed, subdivided into 223 UHRH, taking into account physiographic and hydrometeorological variables. This structuring, already applied by [7], [10], [13] and [4], makes it possible to obtain results that are closer to reality.

UHRHs offer a double advantage: simplifying the representation of physiographic variability while generating differentiated hydrological responses within the basin ([7], [9], [14]). The operation of the basin is thus assimilated to a set of interconnected reservoirs; each unit being modelled individually ([18]). This approach has been applied by Flügel (1996), in [19] in the Bröl basin in Germany, and in various basins around the world such as the Orb in France, the N'zi and Bandama in Côte d'Ivoire, or the Cau in Vietnam, to simulate surface flows ([10], [1], [20], [12], [13], [4]). In Canada, [7] have adopted the same approach for the Chaudière Basin in Quebec. However, some methodological observations remain relevant: the size of UHRHs is arbitrary and their number is limited by computing capacity, which is a constraint to be taken into account when modelling. Nevertheless, UHRH slicing is a robust approach to represent the spatial variability of hydrological processes and improve the accuracy of watershed simulations.

4.2. Performance of the HYDROTEL hydrological model

The cross-simulation period carried out includes the calibration and validation phases in addition to the year 1991 in order to have a five-year period (1991-1995). The results obtained at the outlet station are 0.62 for NS and -0.23% for VE, and the observed and simulated water sheets are respectively 532 mm and 533 mm, over the entire basin during these five years. For the Diabouo and Gagnoa-Issia road stations, the optimization criteria are 0.58 and 0.57 respectively for the NS, and -2.02% and -0.17% for the EV. However, the observation of hydrographs and simulated over the validation period (1994-1995) shows an overestimation during low water periods, which contrasts with a slight underestimation during flood periods. This paradox shows that the emptying of the aquifers takes place with a certain delay that [21] qualifies as the "memory effect".

4.3. Recharge control factors and robustness of modelling

The sensitivity analysis of the potential recharge of the Davo River aquifer, carried out through multiple linear regression and Monte Carlo simulations, highlighted the preponderant role of actual evapotranspiration (REE) and open forest occupation on the spatial variability of recharge. These results confirm that REE is a key endpoint, analogous to the evapotranspiration coefficient (CETP) studied in the BV3C sub-model of HYDROTEL ([1], [4]). The optimization of this parameter strongly conditions the performance of the model, as evidenced by the variation of the Nash-Sutcliffe criterion around optimal values (NS ≈ 0.62–0.65), reflecting the major influence of atmospheric fluxes on the water balance and recharge.

The positive effect of open forest on recharge may seem paradoxical, but it reflects a local water balance in the sense that these more open formations allow for increased infiltration and limit interception, thus increasing net recharge. On the other hand, neither the average slope nor the dense forest emerges as significant determinants, probably because of collinearities or compensations between runoff and infiltration, which is in line with the observations made in other tropical basins ([22]).

The median recharge estimate (140.8 mm/year) and its confidence interval (112–172.7 mm/year), with a moderate coefficient of variation (13.4%). The values obtained are in agreement with previous estimates reported in the Sudano-Guinean zone, generally between 100 and 200 mm/year, reinforcing the validity of the results from the HYDROTEL model. This demonstrates the robustness of the modelling carried out, while highlighting the spatial variability induced by soil textures and land cover as reported [7] and [10]. Thus, the integration of sensitivity analyses and simulations with HYDROTEL modeling gives high confidence to the results, while providing precise indications on the physiographic and climatic factors determining the recharge.

4.4. Potential recharge of aquifers

The results obtained with the HYDROTEL model in the Davo watershed (167–282 mm/year, or an average of 221 mm/year, corresponding to 18.5% of annual rainfall) are similar to those reported by [4] in the Haute Marahoué basin, which placed the recharge at around 19.6% of the annual rainfall with the same HYDROTEL model. They are also higher than estimates of [23] in the N'zo basin (3–6%), thus confirming that modelled recharge varies significantly according to local hydrological and soil characteristics, but tends to be better represented by integrated models. Moreover, these results are similar to several studies that have highlighted the limits of classical empirical methods (Thornthwaite, Turc), including those of [24] and [25] which have shown that they oversimplify the division of water surpluses between runoff and infiltration.

On the other hand, some annoyances appear. The estimated recharge values for BVRD remain lower than those reported by [24] in the N'zi basin (32%) and by [26] Saley (2003) in Man (23%). These differences can be attributed to differences in rainfall conditions, spatial distribution of the data, or distinct geological contexts that modulate infiltration. In the case of this study, this discrepancy is linked to the number and presence of rainfall measurement stations within the BVRD. They emphasize that, even with high-performance models such as HYDROTEL, the transposability of results from one basin to another remains limited without taking into account the specificity of local environments.

Thus, the estimates obtained in the BVRD are generally in line with the work using HYDROTEL, while revealing certain divergences with other studies conducted in different contexts. This double reading highlights the importance of contextualizing the application of hydrological models and systematically confronting their results with local specificities. The approach with the models is intended to be more realistic, either by taking into account more or less parameters related to surface conditions depending on the model, or by having a sophisticated calculation procedure that takes into account the dynamics of the flow process in the soil. The HYDROTEL model, which has made it possible to achieve such results, is a good example of this. Indeed, the consideration of the heterogeneities of the surface finishes through the UHRH and also the daily time step with which the calculations are made, explain why the results with this model are different from the results obtained by other approaches. However, certain factors can explain the low recharge values, for example low rainfall or a poor spatial distribution of the data measured in situ or a complex geological environment limiting infiltration, etc.

5. Conclusion

The approach adopted with HYDROTEL combines a quantitative estimation of the average recharge, the assessment of its uncertainty, the identification of sensitivity parameters and the integration of anthropogenic pressures. This approach is a significant improvement over previous empirical methods (simplified water balances, rainfall indices), by offering a more realistic and spatially explicit representation of the hydrological functioning of the Davo basin. It thus provides a robust basis to guide the sustainable management of water resources in the Ivorian Southwest.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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