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Using Geostatistical Kriging for Hydrologic Models' Parameters Estimation on Niger River Watersheds in West Africa

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Abstract

Geostatistical Kriging is performed on hydrologic model parameters in a two-dimensional region—different from the geographical space—as a hydrospace. The x-axis in percent is a relative difference of soil characteristics between an embedded 12 watersheds in reference to a large one related to the Niger River in West Africa; noted var_WHC, it stands for Water Holding Capacity. The y-axis in percent, var_Nash, is a hydrologic model's efficiency in two contexts: (a) calibrated model parameters on the reference watershed are injected in modelling on each sub-watershed in validation phase to produce a series of Nash values as references, (b) a second series of Nash values is produced in calibrations. SimulHyd which stands for Simulation of Hydrological Systems is applied along with a French hydrological model—Genie Rural with 2 parameters at Monthly time step. The built Nash-WHC hydrospace and its two variants, or hybrids, permit the krige of both hydrologic model's parameters. The relative variation of upper module absolute ranges from 0.1% to 15.68%—the developed hydro-geostatistics practice is considered in reference to hydrological calibration. Accepted as hydrogeostatistics practice, it is applicable to ungauged watersheds to estimate hydrologic models' parameters.

Keywords

Hydrogeostatistics Practice, Niger River, SimulHyd, Hydrospace, GR2M, Hydrological Modelling

1. Introduction

Geostatistics literature scarcely explores the possibility of performing studies in spaces other than the traditional geographical one. Georges Matheron [1], in his foundational works on Geostatistics, explicitly states that variographical analysis and Kriging are exclusively undertaken in the traditional geographical space. Difficulties in leading structural analyses with variographical points could justify his statement. However, unsolved problems such as estimating hydrologic model parameters on ungauged basins instilled the idea of surpassing this statement to fill this research gap. Besides, such a problem leads us to treat model parameters as statistics variables when making estimations on ungauged hydrometric watersheds. The Kriging capability to solve this listed issue among the 23 unsolved hydrological problems [2] motivates the current paper.

2. Materials and Methods

The study is based on the Niger River in West Africa, and data in **Table 1** have been recently described in our previous paper [3] [4]. Some succinct resumes of variables and parameters in columns are following: Δ%_WHC (or var_WHC) represents a relative variation of a soil's characteristics and stands for Water Holding Capacity. Δ%_Nash (or var_Nash) criterion is a relative variation between two Nash estimations: from direct calibration and from Injecting (X1, X2) obtained through calibration at the main hydrometric station, Koulikoro. WHC stands for soil's Water Holding Capacity (WHC) and is extracted from raster's attribute tables present in SIEREM database [5]; SIEREM stands for *Système d'Informations Environnementales sur les Ressources en Eaux et leur Modélisation* (in French). We mainly use the R language [6] in this paper as geostatistical tools for statistics, variograms building and Kriging.

2.1. Statistical Characteristics of Data

The Variabilities in variables, Δ%_WHC and Δ%_Nash, are higher than in parameters, X1 and X2, as demonstrated in **Table 1** through the coefficient of variation, in the last row. Besides, Δ%_WHC has less variability than Δ%_Nash, whereas X1 has more than X2: respectively 70% versus 78%, and 12% versus 8%. In reference to Δ%_WHC with 70% as variability, Δ%_Nash has an increase of 12% (to reach 78%) and both parameters (X1, X2) have some decreases respectively of 83% (to reach 12%) for X1 and of 89% (to reach 8%) for X2.

- *Variables*, *Δ%_ WHC and Δ%_Nash*

Variables in the first two columns of **Table 1**, Δ%_WHC and Δ%_Nash, are statistically elucidated in Section 3 to build hydrospaces. Parameters in its last two columns, X1 and X2, are statistically studied below.

- *Hydrologic model Parameters*, *X*1 *and X*2

Using t.test () function in R language, there is no significant evidence that the two means are statistically different—and the p-value of the related t-statistics equals 0.4; therefore, there is similarity between both means, X1 and X2 parameters. In practice, the test fails to reject the assumption that the difference between both means, X1 and X2, equals zero. Hence, we commit an error of the second specie, in assuming that the 95% confidence interval of means difference is [−3.718; 1.480]; in percent, mean values from samples are respectively 53.69 for X1 parameter, and 54.81 for X2.

Using var.test () function in R language, there is significant evidence that the two variances are statistically different—and the p-value of the related F-statistics equals 0.01; therefore, there is dissimilarity between both variances, X1 and X2 parameters. In practice, the test succeeds in rejecting the assumption that the ratio between both variances, X1 and X2, equals one. Hence, we commit an error of the first specie in assuming that the 95% confidence interval of this ratio is [1.222 4.798]; the mean ratio of variances from samples is 2.422.

Table 1. Statistical summaries of variables and parameters. Δ%_WHC represents a relative variation of a soil's characteristics and stands for Water Holding Capacity. Δ%_Nash criterion is a relative variation between two Nash estimations: from direct calibration and from Injecting (X1, X2) obtained through calibration at the main hydrometric station, Koulikoro.

Dat Statistics	Variables [%]		Parameters [%]	
	Δ%_WHC	Δ%_Nash	X1	X2
Count	35	35	35	35
Summary				
Min.	0.00	0.00	41.6	47.2
1st Qu.	2.05	1.40	48.9	51.8
Median	7.82	3.52	52.9	54.2
Mean	6.74	4.21	53.7	54.8
3rd Qu.	10.98	7.18	59.0	58.4
Max.	15.19	11.38	66.7	63.2
Variability				
Coef. of variation (cv)	70	78	12	8

2.2. Graphical Visualization of Data

We expose statistical characteristics of data in graphics to eventually detect outliers. In Figure 1, The Δ%_Nash variable doesn't demonstrate an outlier value—similar to the other variable, Δ%_WHC, and to the parameters (X1, X2). To further estimate this set of parameters (X1, X2) on ungauged watersheds, each parameter is studied as a regionalized variable in built hydrospaces in Section 3—which are different from the traditional geographic space. Parameters (X1, X2) are at the top right in Figure 1, whilst both variables, Δ%_WHC and Δ%_Nash, are in the bottom left. These variables are presented and elucidated in Section 3.

In Figure 1, both variables have their median values between 3% and 9%, and we observe no outlier point relative to them. Parameters have their median values around 52% to 55%.

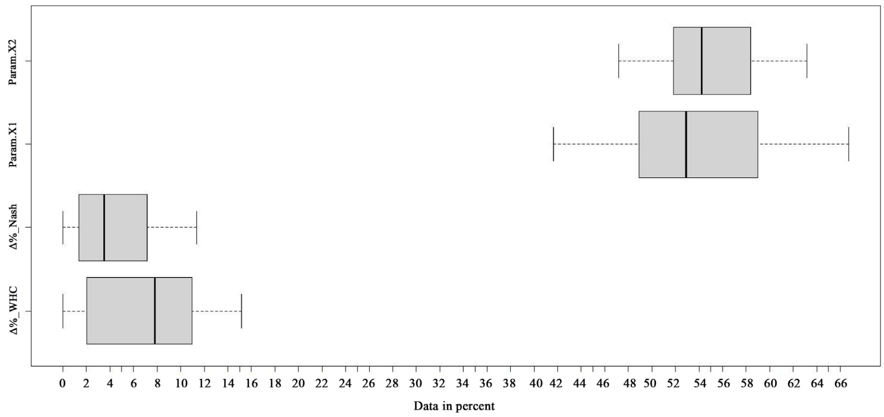

Figure 1. Statistical ranges of variables and parameters (sample size is 35). Δ%_WHC represents a relative variation of a soil's characteristics and stands for Water Holding Capacity. Δ%_Nash criterion is a relative variation between two Nash estimations: from direct calibration and from Injecting (X1, X2) obtained through calibration at the main hydrometric station, Koulikoro.

3. Results and Discussion

Our purpose is to build hydrospaces to estimate hydrologic models' parameters there—these are different from the traditional geographic space. The main hydrospace is built by taking Δ%_WHC variable as the x-axis and Δ%_Nash variable as the y-axis. Linear regression is performed between both axes, and the variability inside the built hydrospace is measured by the residual standard error of 2.923. When taking into account the 68 degrees of freedom, we obtain 4.08 as residual standard error. Relatively to the y-axis, the average deviation is therefore 69% (or 97%) as demonstrated in Figure 2; in such a study, this high value is not an aberration.

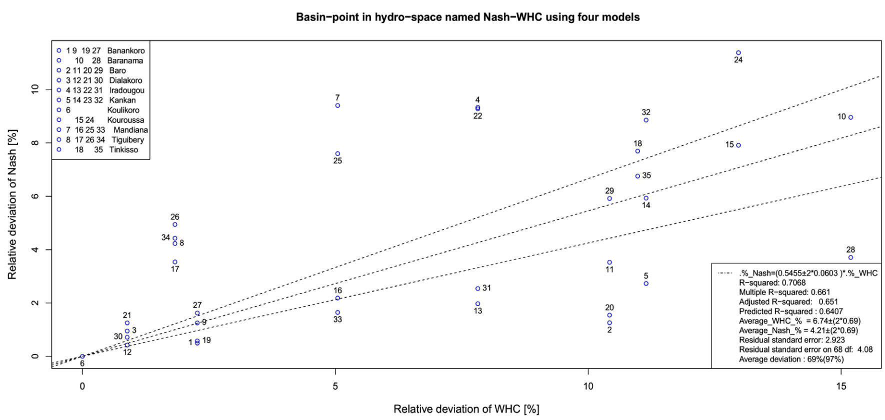

Figure 2. Structural representation of Nash-WHC hydrospace.

3.1. Statistical Characteristics of the Built Hydrospace

Using t.test () function in R language, there is significant evidence that the two means are statistically different—and the p-value of the related t-statistics equals 0.01; therefore, there is dissimilarity between both means, Δ%_WHC and

Δ%_Nash. In practice, the test succeeds in rejecting the assumption that the difference between both means, Δ%_WHC and Δ%_Nash, equals zero. Hence, we commit an error of the first specie in assuming that the 95% confidence interval of means difference is [0.5808; 4.4848]; mean values of samples are respectively 6.741 for Δ%_WHC, and 4.208 for Δ%_Nash.

Using lm () function in R language (through graphics package), the standard error of both variables is 0.69; the population average mean value on x-axis is 6.74 ± (2 * 0.69), and on y-axis it is 4.21 ± (2 * 0.69). Therefore, their respective 95% confidence intervals are [5.36; 8.12] for Δ%_WHC, and [2.83; 5.59] for Δ%_Nash.

Using var.test () function in R language, there is significant evidence that the two variances are statistically different—and p-value of the related F-statistics equals 0.04; therefore, there is dissimilarity of both variances, Δ%_WHC and Δ%_Nash. In practice, the test succeeds in rejecting the assumption that the ratio between both variances, Δ%_WHC and Δ%_Nash, equals one. Hence, we commit an error of the first specie in assuming that the 95% confidence interval of this ratio is [1.038, 4.075]; samples' ratio of variances is 2.057.

Using cor.test () function in R language, there is significant evidence that the two variables are correlated—and the p-value of the related F-statistics equals 7e-04. There is a linear correlation between both variables, Δ%_WHC and Δ%_Nash. In practice, the test succeeds in rejecting the assumption that Pearson's correlation between both variables, Δ%_WHC and Δ%_Nash, equals zero. Hence, we commit an error of the first specie in assuming that the 95% confidence interval of Pearson's correlation is [0.2611; 0.7444]; this correlation is estimated through samples to be 0.5468.

In addition, t-statistics relative to the regression line's slope indicates—through using lisfit () function in R language—there is significant evidence that the slope is not equal to zero; the associated p-value equals zero. We conclude a linear correlation between both variables, Δ%_WHC and Δ%_Nash. In practice, we succeed in rejecting the assumption that the slope is null. The related t-test to the linear regression has been highly significant and the standard error on the slope has been 0.0603. Hence, we commit an error of the first specie in assuming that the 95% confidence interval of the regression line' slope is [0.4249; 0.6661]. The regression line in the Nash-WHC hydrospace is following:

$$\Delta\%\_Nash = (0.5455 \pm 2 * 0.0603) * \Delta\%\_WHC \quad (1)$$

3.2. Structural Characteristics of Built Nash-WHC Hydrospace and Its Variants or Hybrids

The precedent sub-section reveals a linear correlation between both coordinates of the Nash-WHC hydrospace, Δ%_WHC and Δ%_Nash (**Figure 2**). However, Kriging demonstrates the necessity to consider a three polynomial degree relation between coordinates [6], as this trending appears on simulated maps [7] (p.95-96n, in French). The structural equation—variogram—is further built using residuals after trend-fitting through fit.trend () function in R language. Statistics in

Figure 2 are thoroughly elucidated in the precedent sub-section.

Further, a first variant of the hydrospace considers X1 parameter in percent in lieu and place of Δ%_Nash as y-coordinate, in order to krige the X2 parameter. Similarly, the second variant of the hydrospace considers X2 parameter in percent in lieu and place of Δ%_Nash as y-coordinate in order to krige the X1 parameter. These two hybrid hydrospaces or variants, X2-WHC and X1-WHC, don't demonstrate a spatial tendance; they are exploited in Subsection 3.4 to build two variograms, for X1 and X2 parameters.

3.3. Variogram-Hydrologic Model Parameters in Nash-WHC Hydrospace

Experimental variogram points reveal the spatial structure of X1 and X2 parameters in Nash-WHC hydrospace, as exposed in Figure 3 and Figure 4. These variograms express structural equations and serve as models to do mappings further.

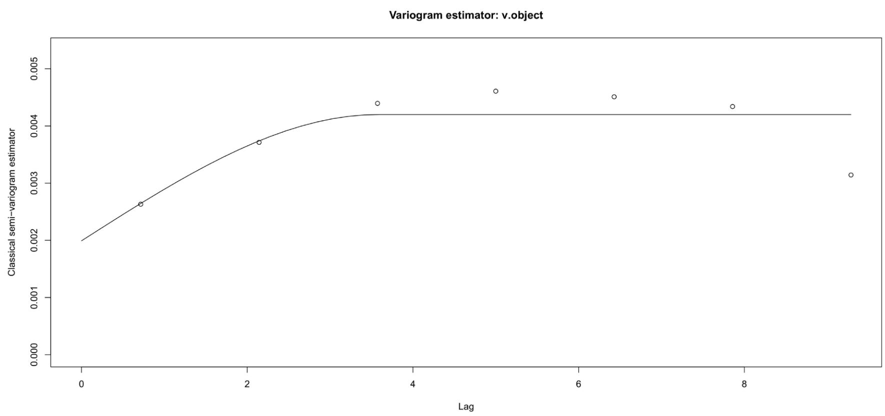

Figure 3. Variogram of X1 parameter using residuals in Nash-WHC hydrospace.

3.3.1. Variogram of X1 Parameter in Nash-WHC Hydrospace

As shown in Figure 3, fitted variographical model has the following characteristics:

Experimental Variogram: classical

Variogram type: spherical

Nugget value (c0): 0.0019919 [$\%^2$]

Sill (c): 0.0022074 [$\%^2$]

Range (a): 3.5746 [%]

The kriged map of X1 parameter in Nash-WHC hydrospace is exposed and discussed in the section on practice of hydrogeostatistics.

3.3.2. Variogram of X2 Parameter in Nash-WHC Hydrospace

As shown in Figure 4, fitted variographical model of X2 parameter has the following characteristic:

Experimental Variogram: classical

Variogram type: gaussian

Nugget value (c0): 0.00091796 [$\%^2$]

Sill (c): 0.0009606 [$\%^2$]

Range (a): 4.3748 [%]

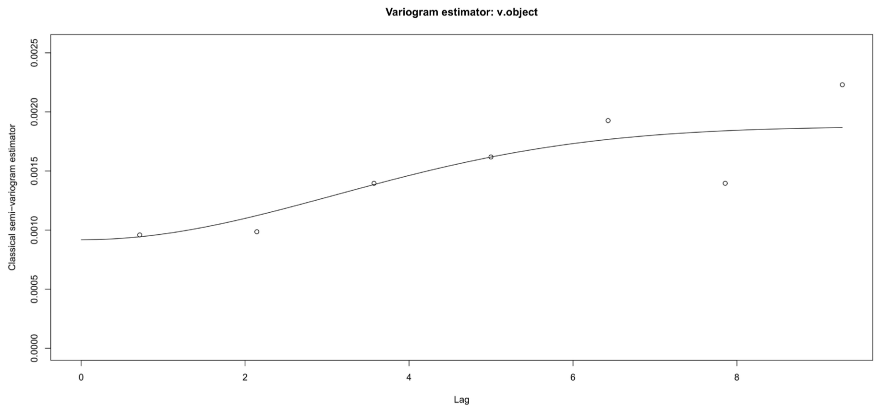

Figure 4. Variogram of X2 parameter using residuals in Nash-WHC hydrospace.

The kriged map of X2 parameter in Nash-WHC hydrospace is exposed and discussed in the section on practice of hydrogeostatistics.

3.4. Variogram of Hydrologic Model Parameters in Hybrid Hydrospaces: X1-WHC and X2-WHC

Two hybrids of the hydrospace that consider alternatively X1 and X2 parameters in percent in lieu et place of Δ%_Nash y-coordinate, are respectively coined in this paper as X2-WHC hydrospace and X1-WHC hydrospace. Structural information on both parameters in these hydrospaces is in the following subsections.

3.4.1. Variogram of X1 Parameter in a Hybrid Hydrospace: X2-Nash

As shown in Figure 5, fitted variographical model has the following characteristics:

Experimental Variogram: classical

Variogram type: spherical

Nugget value (c0): 0.0021364 [%^{2}]

Sill (c): 0.0017608 [%^{2}]

Range (a): 3.2803 [%]

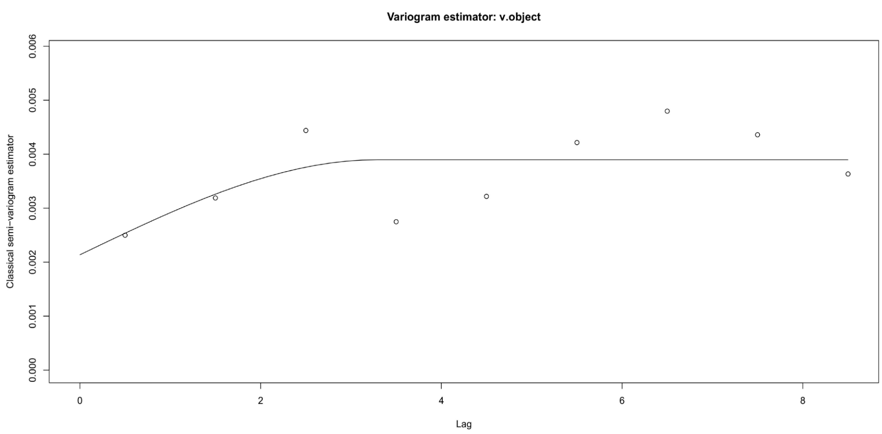

Figure 5. Variogram of X1 parameter in X2-WHC hydrospace.

The kriged map of X1 parameter in X2-WHC hydrospace is exposed and discussed in the section on practice of hydrogeostatistics.

3.4.2. Variogram of X2 Parameter in a Hybrid Hydrospace: X1-Nash

As shown in Figure 6, fitted variographical model has the following characteristics:

Experimental Variogram: robust

Variogram type: gaussian

Nugget value (c0): 0.0005651 [$\%^2$]

Sill (c): 0.0017986 [$\%^2$]

Range (a): 6.1694 [%]

The kriged map of X2 parameter in X1-WHC hydrospace is exposed and discussed in the section on practice of hydrogeostatistics.

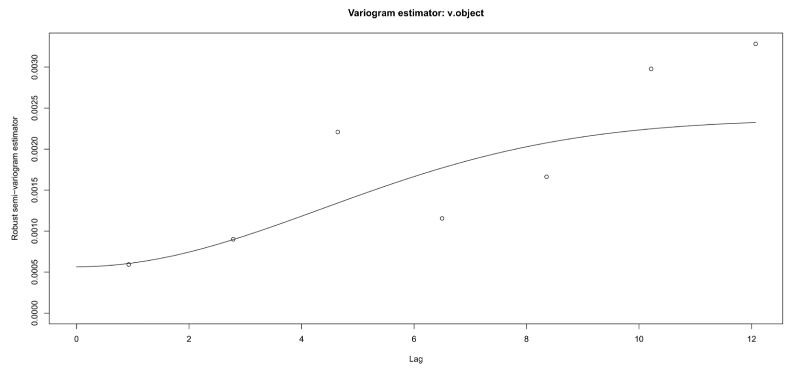

Figure 6. Variogram of X2 parameter in X1-WHC hydrospace.

3.5. Hydrogeostatistics—Producing Hydrologic Model Parameters on Ungauged Watersheds

A two-step protocol leads to the production of hydrologic model parameters through practicing hydrogeostatistics theory. Firstly, y-axis coordinate of the Nash-WHC hydrospace, Δ%_Nash, is estimated through equations related to Figure 7—the x-axis coordinate, Δ%_WHC, is pre-determined for a watershed as exposed in Section 2—through methods described in [5]. Secondly, we evaluate the potential values of set parameters (X1, X2) for a point-basin model in built hydrospaces.

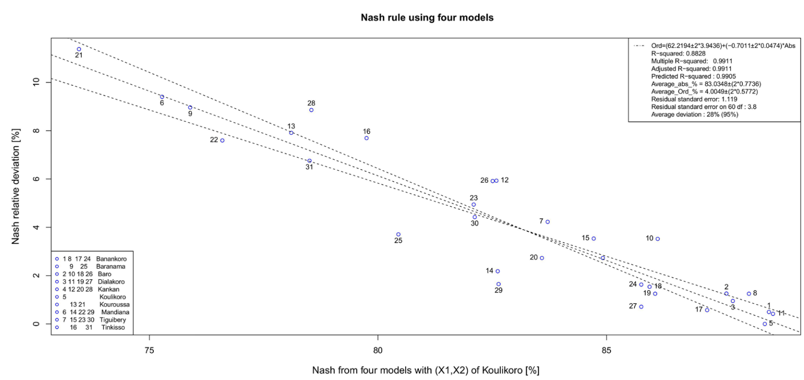

Figure 7. Rule to estimate the ordinate Δ%_Nash of the Nash-WHC hydrospace (31 samples).

3.5.1. Rule to Estimate the Ordinate of the Nash-WHC Hydrospace

The correlation inside the hydrospace is appreciated through Residual standard error of linear regression as 1.119—and when taking into account the degree of freedom (df), we obtain 3.8 on 60 df. Relatively to y-axis's mean value and regression line the average deviation is therefore 28% (95%). In practice—for each value of x-axis in Figure 7 (obtained through 31 samples)—we derive the y-axis value through the following equation:

$$\Delta\%\_Nash = (62.2194 \pm 2 * 3.9436) + (-0.7011 \pm 2 * 0.0474) * \Delta\%\_WHC \quad (2)$$

The median value out of the nine derived variant equations from (2) that produce positive values could be considered. Hence, the following formula could be adopted to estimate Δ%_Nash, the ordinate, or y-coordinate:

$$\Delta\%\_Nash = (62.2194) + (-0.7011 + 2 * 0.0474) * \Delta\%\_WHC \quad (3)$$

The coefficient of variation produced through Equation (3) on a set of seven watersheds, has the median value (32%) in comparison to the other equations that produce reliable positive values of Δ%_Nash. However, Equation (4) below has 133% as coefficient of variation—the lowest of both highest values out of nine. It serves to estimate hydrologic model parameters in Table 2 and Table 3 through practicing our hydrogeostatistics theory.

$$\Delta\%\_Nash = 62.2194 - 0.7011 * \Delta\%\_WHC \quad (4)$$

3.5.2. Kriged Maps of Hydrologic Model Parameters in Hydrospaces

kriged maps in Figure 8 and Figure 9 pertained both to X1 parameter's estimations; they are produced respectively through variograms in Figure 3 in Nash-WHC hydrospace and in Figure 5 in X2-WHC hydrospace. The last two kriged maps (Figure 10 and Figure 11) are from variograms in Figure 4 and Figure 6 and provided respectively in Nash-WHC hydrospace and in X1-WHC hydrospace; they pertained both to X2 parameter's estimations.

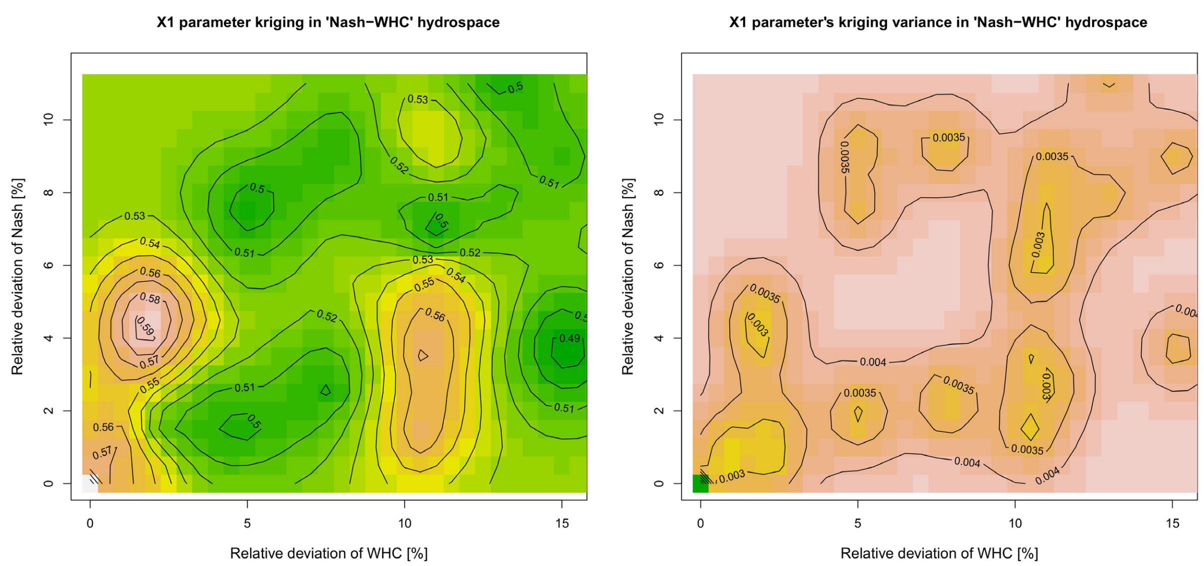

Figure 8. Kriged map of the X1 parameter in Nash-WHC hydrospace (left) and its Kriging variance (right).

Kriged maps are built using estimates in discretized hydrospaces; hence, Figure 8 and Figure 10 use both 1863 hydro-spatial nodes in Nash-WHC hydrospace, whilst Figure 9 and Figure 11 use respectively 2592 in X2-WHC hydrospace and 4131 hydro-spatial nodes in X1-WHC hydrospace.

- *hydrologic model's $X1$ value versus hydrogeostatistics' $X1$ estimate*

Kriged maps of the X1 parameter are produced through variograms on Figure 3 and Figure 5 obtained respectively in Nash-WHC hydrospace and X2-WHC hydrospace.

-Kriged $X1$ parameter in Nash-WHC hydrospace

The Nash-WHC hydrospace coordinates in Figure 8 are:

y-axis: Δ%_Nash

x-axis: Δ%_WHC

Variogram for Kriging: Figure 3

Test hydrometric station: Banankoro (in Mali)

Simulation period: 1971-1999 (with 31% as a gap in hydrometric data)

X1 parameter value from Hydrologic model SimulHyd semi-distributed: 0.59085

X1 as a hydrogeostatistics' estimate in Nash-WHC hydrospace: 0.55126

Relative variation between both values of X1 parameter: −6.70%

-Kriged $X1$ parameter in $X2$-WHC* hybrid *hydrospace

The Nash-WHC hydrospace coordinates in Figure 9 are:

y-axis: X2 parameter in percent

x-axis: Δ%_WHC

Variogram for Kriging: Figure 5

Test at hydrometric station: Banankoro (in Mali)

Simulation period: 1971-1999 (with 31% as a gap in hydrometric data)

X1 parameter value from Hydrologic model SimulHyd semi-distributed: 0.59085

X1 as a hydrogeostatistics' estimate in X2-WHC hydrospace: 0.5593

Relative variation between both values of X1 parameter: −5.34%

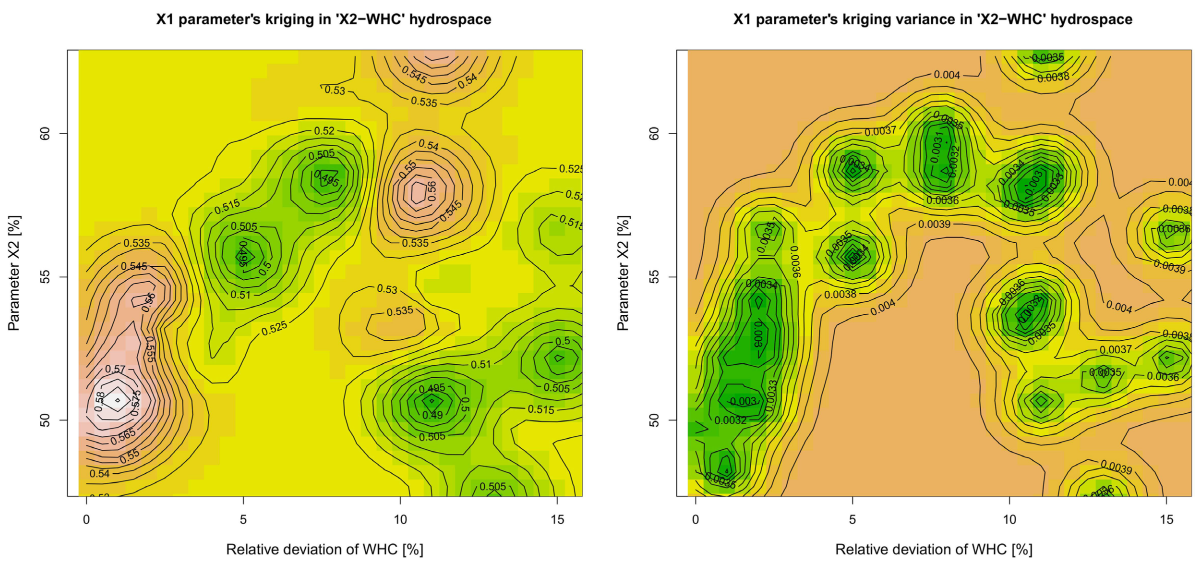

Figure 9. Kriged map of the X1 parameter in X2-WHC hydrospace (left) and its Kriging variance (right).

- *Hydrologic model's X2 value versus hydrogeostatistics' X2 estimate*

Kriged maps of the X2 parameter are produced through variograms in Figure 4 and Figure 6 obtained respectively in Nash-WHC hydrospace and X1-WHC hydrospace.

-Kriged X2 parameter in Nash-WHC hydrospace

The Nash-WHC hydrospace coordinates in Figure 10 are:

y-axis: Δ%_Nash

x-axis: Δ%_WHC

Variogram for Kriging: Figure 4

Test hydrometric station: Banankoro (in Mali)

Simulation period: 1971-1999 (with 31% as a gap in hydrometric data)

X2 parameter value from Hydrologic model SimulHyd semi-distributed: 0.54525

X2 as a hydrogeostatistics' estimate in Nash-WHC hydrospace: 0.5274

Relative variation between both values of X2 parameter: −3.27 %

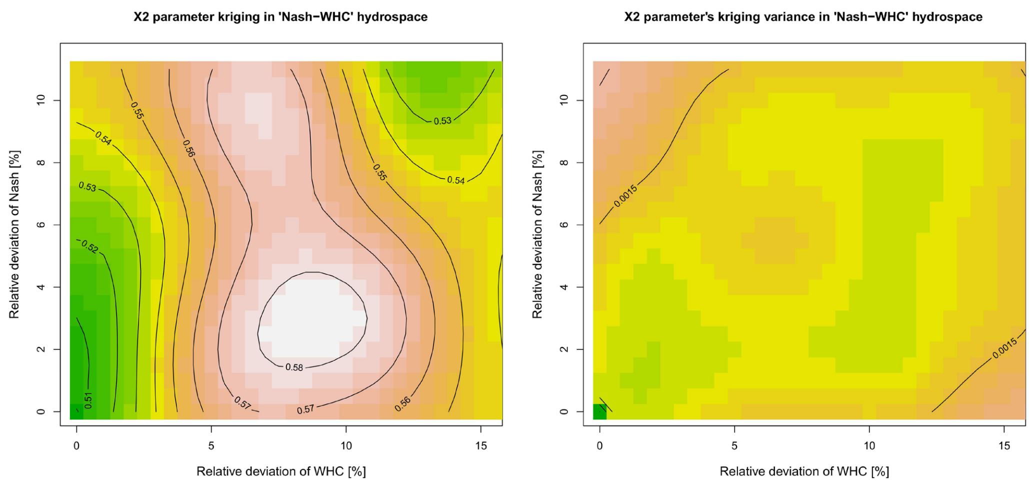

Figure 10. Kriged map of the X2 parameter in Nash-WHC hydrospace (left) and its Kriging variance (right).

-Kriged X2 parameter in X1-WHC hybrid hydrospace

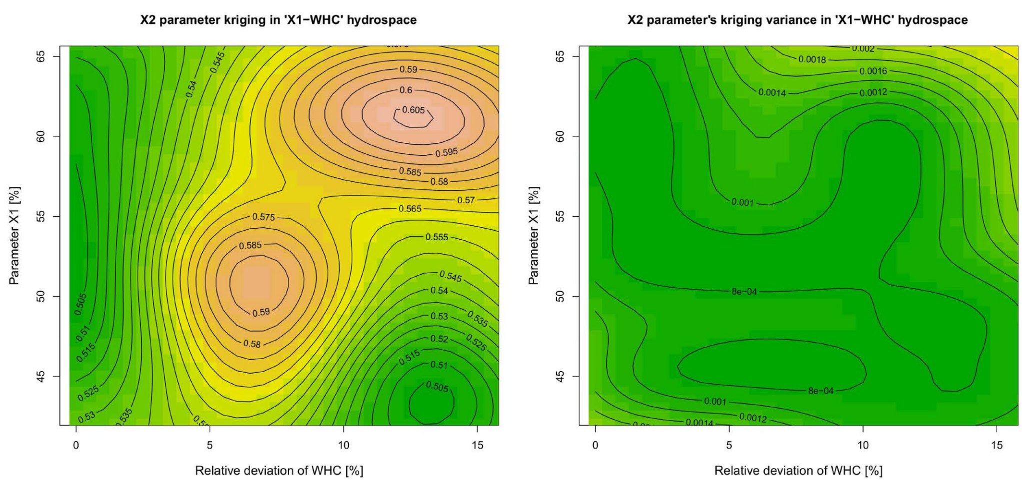

Figure 11. Kriged map of the X2 parameter in X1-WHC hydrospace (left) and its Kriging variance (right).

The Nash-WHC hydrospace coordinates in Figure 11 are:
y-axis: X1 parameter in percent
x-axis: Δ%_WHC
Variogram for Kriging: Figure 6
Test at hydrometric station: Banankoro (in Mali)
Simulation period: 1971-1999 (with 31% as a gap in hydrometric data)
X2 parameter value from Hydrologic model SimulHyd semi-distributed: 0.54525
X2 as a hydrogeostatistics' estimate in X1-WHC hydrospace: 0.5265
Relative variation between both values of X1 parameter: −3.44%

3.6. Summary

To resume, we extract from hydro-spatial nodes the estimated values of X1 and X2 parameters in Nash-WHC hydrospace, alternatively in X2-WHC or in X1-WHC hydrospaces. Coordinates (Δ%_WHC, Δ%_Nash) of a point-basin in Nash-WHC hydrospace are previously estimated as explained in Subsections 3.5 and 3.5.1. The x-axis coordinate of a point is the same for the three mentioned hydrospaces.

Table 2 resumes parameters's estimations at three hydrometric stations (Banankoro, Kankan and Mandiana) using the developed hydrogeostatistics practice in comparison to calibration in hydrological modelling.

Forming a set (X1, X2) from estimated parameter's values from both in X1-WHC hydrospace and in X2-WHC hydrospace is possible on watersheds as demonstrated in Table 2 and Table 3 as variant v1. Table 3 delivers insight both in terms of water balance and in terms of relative variation of modules and peaks, simulated versus observed. There, the second columns, Upper Module Absolute criteria, demonstrate that its relative variation—when considering Hydrogeostatistics practice in reference to calibration—ranges from 0.1% to 15.68%; median and mean values are respectively 9.28% and 8.26%; interquartile range is 9.655%.

Table 2. Hydrogeostatistics practice with 35 as sample size in hydrospaces—hydrologic model's parameters against their produced ones through hydrogeostatistics practice. Two variants are produced: (variant V0), both X1 and X2 parameters are produced in Nash-WHC hydrospace; (variant V1), X1 parameter is produced in X2-WHC hydrospace and X2 parameter is produced in X1-WHC hydrospace. Nash criteria, the objective function during calibration is still applied in validating produced parameters through hydrogeostatistics practice.

Calibration			Hydrogeostatistics practice: 35 and 31 samples respectively in hydrospaces and for Nash rule			
Parameters		Nash	Variants	Parameters		Nash
X1	X2	Criteria		X1	X2	Criteria
Banankoro station; SimulHyd Semi-Distributed model; 1971-1999; Gap 31%						
0.59085	0.54525	88.993	v0	0.55126	0.5274	86.904
			v1	0.5593	0.5265	87.558
Kankan station; SimulHyd Semi-Distributed model; 1950-1995; Gap 4%						
0.58897	0.63168	87.305	v0	0.56458	0.5785	86.031
			v1	0.56273	0.56891	85.693
Mandiana station; SimulHyd Semi-Distributed model; 1957-1995; Gap 29%						
0.52041	0.58599	83.093	v0	0.51157	0.56923	82.900
			v1	0.50095	0.58243	82.610

Table 3. Hydrogeostatistics practice with 35 as sample size in hydrospaces—Semi-distributed SimulHyd hydrologic model's performances using its calibrated parameters against its performances through hydrogeostatistics practice. Two variants are produced: (variant V0), both X1 and X2 parameters are produced in Nash-WHC hydrospace; (variant V1), X1 parameter is produced in X2-WHC hydrospace and X2 parameter is produced in X1-WHC hydrospace. Nash criteria, the objective function during calibration, is still applied in validating produced parameters through hydrogeostatistics practice.

Calibration				Variants	Hydrogeostatistics practice: 35 and 31 samples respectively in hydrospaces and for Nash rule			
Balance [mm]		Relative variation Between [%]			Balance [mm]		Relative variation Between [%]	
Upper Module	Upper Module Absolute	Modules	Peaks		Upper Module	Upper Module Absolute	Modules	Peaks
Banankoro station; SimulHyd Semi-Distributed model; 1971-1999; Gap 31%								
184	997	14	−19	v0	788	1109	2	−28.512
				v1	681	1070	5	−26.975
Kankan station; SimulHyd Semi-Distributed model; 1950-1995; Gap 4%								
1039	3795	5	−13	v0	2466	4304	0	−20.299
				v1	2619	4390	−1	−21.173
Mandiana station; SimulHyd Semi-Distributed model; 1957-1995; Gap 29%								
368	1906	11	−19	v0	612	1908	9	−22.158
				v1	796	1941	6	−23.684

Our Hydrogeostatistics practice is therefore necessary in cases where poor observed data leads to improper hydrologic modelling or the hydrometric stations are still ungauged. Such Kriging in new hydrospaces is barely discussed in hydrological modelling fields. Upper Module Absolute criteria are widely applied in literature when assessing water balance during peak seasons [8]-[10].

When enhancing the sample size from 35 to 50, the hydrometric stations are evaluated along with Kouroussa station in larger hydrospaces (**Table 4** and **Table 5**). Upper Module Absolute criteria's variation—when considering Hydrogeostatistics practice in reference to calibration—ranges from −0.42% to 20.03%; median and mean values are respectively 9.175% and 8.065%; interquartile range is 11.445%.

Doing statistics in combining results from two scales—hydrospaces both with 35 *samples and with* 50 *samples.*

Upper Module Absolute criteria, demonstrate that its relative variation—when considering Hydrogeostatistics practice in reference to calibration—has respectively median and mean values of 9.18% and 8.15%; interquartile range is 11.878%.

When considering variant zero exclusively, these central values are 10.530% for median and 6.886% for mean; interquartile range is 10.85%. Variant 1 has central values of 7.82% as median and 9.41% as mean; its interquartile range is 10.075%.

Limitation of hydrogeostatistics practice

Build hydrospaces have both coordinates in percent relative variation that leads to questioning about which extent these axes could reach as maximum values. Nash-WHC hydrospace with 35 samples has x-axis maximum value of 15.19% and y-axis maximum value of 11.38% (**Figure 2**). Variogram parameters change when working in Nash-WHC hydrospace with 50 samples, which leads to results in **Table 4** and **Table 5**.

Nash rule, Formula 4, established in **Figure 7**, is from 31 samples; it serves in both Nash-WHC hydrospaces and is one possibility out of nine explicitly known formulas. Formulas are dependent on samples size. Moreover, results change as we adopt another formula out of the nine.

Table 4. Hydrogeostatistics practice with 50 as sample size in hydrospaces—hydrologic model's parameters against their produced ones through hydrogeostatistics practice. Two variants are produced: (variant V0), both X1 and X2 parameters are produced in Nash-WHC hydrospace; (variant V1), X1 parameter is produced in X2-WHC hydrospace and X2 parameter is produced in X1-WHC hydrospace. Nash criteria, the objective function during calibration is still applied in validating produced parameters through hydrogeostatistics practice.

Calibration			Hydrogeostatistics practice: 50 and 31 samples respectively in hydrospaces and for Nash rule			
Parameters		Nash Criteria	Variants	Parameters		Nash Criteria
X1	X2			X1	X2	
Banankoro station; SimulHyd Semi-Distributed model; 1971-1999; Gap 31%						
0.59085	0.54525	88.993	v0	0.55064	0.5372	87.069
			v1	0.55782	0.52918	87.502
Kankan station; SimulHyd Semi-Distributed model; 1950-1995; Gap 4%						
0.58897	0.63168	87.305	v0	0.56696	0.5836	86.266
			v1	0.55256	0.57451	85.137
Kouroussa station; SimulHyd Semi-Distributed model; 1950-1995; Gap 33%						
0.51332	0.50995	85.211	v0	0.50111	0.50219	84.928
			v1	0.45934	0.52273	81.399
Mandiana station; SimulHyd Semi-Distributed model; 1957-1995; Gap 29%						
0.52041	0.58599	83.093	v0	0.54219	0.54005	82.516
			v1	0.51611	0.57068	83.009

Table 5. Hydrogeostatistics practice with 35 as sample size in hydrospaces—Semi-distributed SimulHyd hydrologic model's performances using its calibrated parameters against its performances through hydrogeostatistics practice. Two variants are produced (variant V0), both X1 and X2 parameters are produced in Nash-WHC hydrospace; (variant V1), X1 parameter is produced in X2-WHC hydrospace and X2 parameter is produced in X1-WHC hydrospace. Nash criteria, the objective function during calibration, is still applied in validating produced parameters through hydrogeostatistics practice.

Calibration		Hydrogeostatistics practice: 50 and 31 samples respectively in hydrospaces and for Nash rule		
Balance [mm]	Relative variation Between [%]	Variants	Balance [mm]	Relative variation Between [%]

Continued

Upper Module	Upper Module Absolute	Modules	Peaks		Upper Module	Upper Module Absolute	Modules	Peaks
Banankoro station; SimulHyd Semi-Distributed model; 1971-1999; Gap 31%								
184	997	14	−19	v0	769	1102	2	−27.916
				v1	693	1075	4	−27.068
Kankan station; SimulHyd Semi-Distributed model; 1950-1995; Gap 4%								
1039	3795	5	−13	v0	2325	4239	0	−19.592
				v1	3012	4555	−3	−22.639
Kouroussa station; SimulHyd Semi-Distributed model; 1950-1995; Gap 33%								
460	2568	5	−21	v0	897	2590	2	−24.355
				v1	2112	2918	−11	−31.668
Mandiana station; SimulHyd Semi-Distributed model; 1957-1995; Gap 29%								
368	1906	11	−19	v0	65	1913	18	−17.486
				v1	511	1898	10	−21.066

4. Conclusions

Hydrogeostatistics practice, as demonstrated in this paper, leads to estimate hydrologic model parameters using constructed kriged maps. These Krigings are performed in a developed hydrospace coined "Nash-WHC" in this paper—which is different from the traditional geographic space. In addition to the main methodology in Nash-WHC hydrospace, similar kriged maps are developed through two variant hydrospaces namely "X1-WHC" and "X2-WHC".

The x-axis in percent, as noted Δ%_WHC, is a relative difference of soil characteristics between an embedded 10 watersheds in reference to a large one in the study on the Niger River in West Africa, WHC stands for Water Holding Capacity.

The other coordinate, y-axis in percent, is a hydrologic model efficiency, Δ%_Nash, relatively taken in two contexts: (a) the set of model parameters calibrated on the reference watershed (Koulikoro) is injected in modelling on a sub-watershed in validation phase to produce a first criterion as a reference, (b) calibration phase on this sub-watershed is applied to provide a second criterion value.

Hydrologic model SimulHyd is used, which stands for Simulation of Hydrological Systems, is used along with a French hydrological model—Genie Rural with 2 parameters at a Monthly time step.

The relative variation of upper module absolute ranges from 0.1% to 15.68%—when considering the developed hydrogeostatistics practice in reference to calibration in hydrological modelling—and median and mean values are respectively 9.28% and 8.26%. Theorized in this paper as hydrogeostatistics practice, it is applicable to ungauged watersheds to produce estimated parameters for hydrologic models. Its effectiveness is demonstrated on the Niger River as, in some cases, the water balances, obtained with its estimated parameters, are ameliorated in reference to results produced using the initial hydrologic model's parameters.

This work provides hydrogeostatistics practice protocols that are adaptable to other hydrologic models and further to other fields of scientific research to estimate parameters where data are poor in quality or missing.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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