Weak relationships between landforms and hydro-climatologic processes: a case study in Haiti

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ABSTRACT

Our dependence on the continental water cycle (CWC) is such that we clearly need to improve our understanding of its issues from a multidisciplinary perspective. We assess the water resources in an understudied country, Haiti, to estimate the geomorphological (8 variables), hydrological (7), and climatological (7) behaviors of the main (26) watersheds. This generated almost exhaustive knowledge of the surface and sub-surface components of the CWC. In this paper, we intend to integrate these components into a synthetic and coherent view of the environment by looking for relationships between each other. We explore the correlations between several variables (including daily rainfall, river discharge, and river network metrics) of the pre-mentioned water components using robust and rigorous statistical analyses. We found a significant yet weak (spatiotemporal) correlation between the geomorphologic and climatologic components (RV test comparing two datasets with permutations, p-value $= 10^{-3}$). Some partial, weak, and contingent relationships between specific geomorphologic, hydrologic, and climatologic behaviors were apparent too. The final comparison between atmosphere, hydrosphere, and geosphere in Haiti consists in the definition of four watershed categories showing strongly differentiated water cycle behaviors in the country, thus suggesting developing integrated mechanistic models for a multidisciplinary management of the CWC.

Key words | channel network, multiscale behavior, rainfall regime, regionalization, river discharge, watershed

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INTRODUCTION

The continental (terrestrial) water cycle (CWC) can be considered as a complex dynamic system, which remains hard to fully understand. As a proof, the modeling and prediction of precipitations and/or river discharge in specific watersheds is still in its infancy (Hrachowitz *et al.* 2013; De Lavenne *et al.* 2015). These resources are under increasing pressure, considering human population growth as well as global changes (Cincotta *et al.* 2000; Allen & Ingram 2002), leading to a multiscale and multifaceted water security issue (UN Water 2013; Cudennec *et al.* 2014). We therefore urgently need to improve our understanding of this system and its regional subsystems as they constrain the water resources on which humans depend (Huntington 2006; Moors & Stoffel 2013; Cudennec *et al.* 2015). In this synthesis paper, our goal was to build on an extended research project designed to identify correlated processes within the superficial (aerial and surface) part of the regional CWC for an improved management.

Our relatively poor knowledge of the regional (integrated) circulation of water on Earth is quite striking,

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compared to the deep knowledge we have of most processes related to water fluxes (Huntington 2006; Trenberth *et al.* 2007). Most of the water resources required by humankind come from runoff and sub-surface waters, and these water reservoirs are conditioned by the complex relationships between rainfall, the watershed, its geomorphology, and its surface management (Dooge 1986; Allen & Ingram 2002). Some pairwise relationships (spatiotemporal correlations) of this system are now better studied and understood, such as the rainfall–runoff and management–runoff processes (Wooldridge *et al.* 2001; Wagener *et al.* 2007). Yet, we still lack a holistic and unified view of this system. This is a recurrent problem in most empirical sciences, based on a reductionist scheme and fragmented analytical approaches that make it much more difficult to 'integrate' our knowledge at higher levels of organization (Cincotta *et al.* 2000; Huntington 2006; Kriegler *et al.* 2009). Hence, CWC studies must be multidisciplinary and must simultaneously incorporate, as in our study, the atmosphere, hydrosphere, geosphere, and possibly anthroposphere (Houet *et al.* 2010; Moors & Stoffel 2013).

This holistic understanding of the water cycle is essential to predict the fate of the CWC with greater certainty, and thus to optimize our management of water resources, our control of environmental risks. Furthermore, this issue remains valid at all (spatial and temporal) scales. The processes related to the global (e.g. tipping point debate (Kriegler *et al.* 2009; Brook *et al.* 2013; Gaucherel & Moron 2016)), regional (regionalization issue (Chiang *et al.* 2002; Gotzinger & Bardossy 2007)), and even local (rainfall–runoff relationship (Wooldridge *et al.* 2001; Hrachowitz *et al.* 2013)) scales may indeed differ. Such an endeavor attempts to encompass the CWC with multidisciplinary projects designed to simultaneously quantify and understand several components of this complex system, such as geomorphology, ecology, hydrology, climatology, oceanography, and sociology (Montanari *et al.* 2013). As this is virtually impossible in practical terms, we usually define a specific well-instrumented region and try to measure as much data on the CWC as it is possible to gather. In Haiti, we therefore focused on the 'superficial' (i.e. aerial and surface) parts of this CWC.

The project (called BVH, for Haitian watersheds, in French), commissioned by the Haitian government, set two important and complementary objectives: (i) to assess the CWC and water resources in Haiti, an understudied country in this respect, and (ii) to increase the fundamental knowledge of the CWC on a regional scale by inferring possible relationships between diversified earth surface processes. This paper concerns the second goal only (ii), as our aim here was not to extensively present the results (i) of the project. Nevertheless, we will briefly summarize them by describing what we have understood so far concerning the physiognomy and dynamics of the Haitian watersheds. Indeed, several papers on Haiti have already detailed the insights gained from water resources in time (watershed discharges (Gaucherel *et al.* 2016) and rainfall regime (Moron *et al.* 2015)) and in space (the relief (Polidori *et al.* 2014), watershed shapes (Bonhomme *et al.* 2013) and river networks (Gaucherel *et al.* 2017)).

This second objective (ii) can be divided into two clear-cut questions. First, we explored the statistical relationships between the processes involved. On the basis of quite commonly used statistical tools, we intended to achieve a clear multidisciplinary understanding of the CWC in a developing country (CEGET 1985). Indeed, developing countries often show two central weaknesses that should represent major objectives: they need environmental data and, to some extent, they lack the know-how and/or computational resources to implement models that other countries can afford. The central question and innovation here is whether we identified significant relationships in Haiti between geomorphological, hydrological, and climatological variables of instrumented watersheds (i.e. equipped with rain gauges and one hydrological station). The significant relationships found in the project will directly benefit water-related science (Huntington 2006; Hrachowitz *et al.* 2013), as well as the management of Haitian watersheds (e.g. watersheds showing the same properties will favor similar planning). The lack of a relationship found between other components will suggest new directions in studying this complex system. Second, we also set out to integrate the whole CWC and explore the limitations of our understanding of a typical regional water system. This will help to recommend further works on the basis of a conceptual discussion: how can we improve our understanding of the water-related environment of a region such as Haiti, without building huge mechanistic models and powerful computing resources?

MATERIALS AND METHODS

Study area

Haiti is a mountainous Caribbean country located between 18°–20°N and 71°–74°W with an area of about 27,750 km^2 (Figure 1(a)). It is located in the western part of an island (formerly called Hispaniola) shared with the Dominican Republic. Elevations higher than 200 m cover roughly 75% of the country's surface, with the highest peak culminating at 2,680 m above sea level (Pic de la Selle), and more than 80% of the rock lithology is of metamorphic and sedimentary origins (CEGET 1985; Polidori *et al.* 2014; Gaucherel *et al.* 2017). The region's active tectonic dynamics, coupled with the convective nature of tropical rainfall and degraded vegetation cover, make Haiti particularly exposed to several natural risks such as floods, earthquakes, landslides, and erosion. The high human population density (~400 inhabitants/km^2) explains why the country suffers frequently from such natural catastrophes, and thus explains the urgent need for Haiti to estimate its water resource in terms of quantity and quality (Boyer *et al.* 2011; Shamir *et al.* 2013). Haitian hydrology is complex, partly due to the delay between precipitation and runoff, but primarily due to the rugged topography, which also superimposes a complex pattern of sea and plain/mountain breezes on the regional-scale easterlies (Gaucherel *et al.* 2016).

The average annual rainfall has recently been estimated at 1,490 mm on average in the 20th century, 45% of which is thought to generate runoff water (Moron *et al.* 2015; Gaucherel *et al.* 2016). The regional-scale climate of Haiti is, as the whole Caribbean basin, mostly driven by the varying intensity of 'trades' (easterly winds), including the Caribbean low level jet, and associated low-level inversion, which are partly explained by the location and intensity of the subtropical anticyclone (i.e. Azores high) and pressure gradient between the Caribbean basin and Eastern Pacific (Giannini *et al.* 2000; Taylor *et al.* 2002; Jury 2009; Gouirand *et al.* 2014), but also regional-scale sea surface temperatures, which are warmer than 27 °C from May to December around Haiti (Moron *et al.* 2015). Precipitations are widespread from April to November with two peaks in May–June and September–November separated by a relatively dry period, called the mid-summer drought (MSD), centered in July over Haiti (Moron *et al.* 2015). We recently established that the interannual variations of monthly rainfall are mostly shaped by the intensity of the zonal component of the low level winds across the Caribbean sea with drier-(wetter-)than-average rainfall associated with easterly (westerly) anomalies; that is, faster (reduced) trades than usual, and anomalous subsidence (ascent) and low level divergence (convergence) (Moron *et al.* 2015). In addition, it has been observed that there is a dominant influence of the interannual variations of Haitian rainfall by intensity, track, and/or recurrence of tropical depressions traveling NE of Haiti, especially during the second rainy season in August–November.

The relationships between mean annual rainfall on one hand and altitude and slope orientation on the other hand are not trivial. Using the new high resolution (0.05°) rainfall estimates from CHIRPS (Funk *et al.* 2015) with altitude at the same resolution (interpolated from the 30 arc-second dataset http://coastwatch.pfeg.noaa.gov/erddap/griddap/usgsCeSrtm30v6.html) does not show any clear, either linear or quadratic nor more complex, relationship between mean annual rainfall and elevation. In particular, no obvious maximum rainfall at the same elevation across the country is observed (not shown). The only significant signal (T-test p-value = 0.01) is found between mean annual rainfall and aspect: NE (SW) facing slopes; that is, windward (leeward) to the usual trades, are 12.5% wetter (14.1% drier) than the mean rainfall received across the country; the NW facing slopes lead to the same mean rainfall as the country average, while the SE facing slopes are slightly (4.5%) wetter than the country average (T-test p-value = 0.08). This observation may be due to the combination of several factors, among which are the dominant trade system, the varying occurrence and location of cyclones and other rain-bearing systems such as mesoscale clusters, the Dominican Republic shading the Haiti country vs. trade winds, at least for a part of Haiti. In addition, the irregular country shape (as the southern narrow tip may lead to sea–land breeze systems able to counteract the

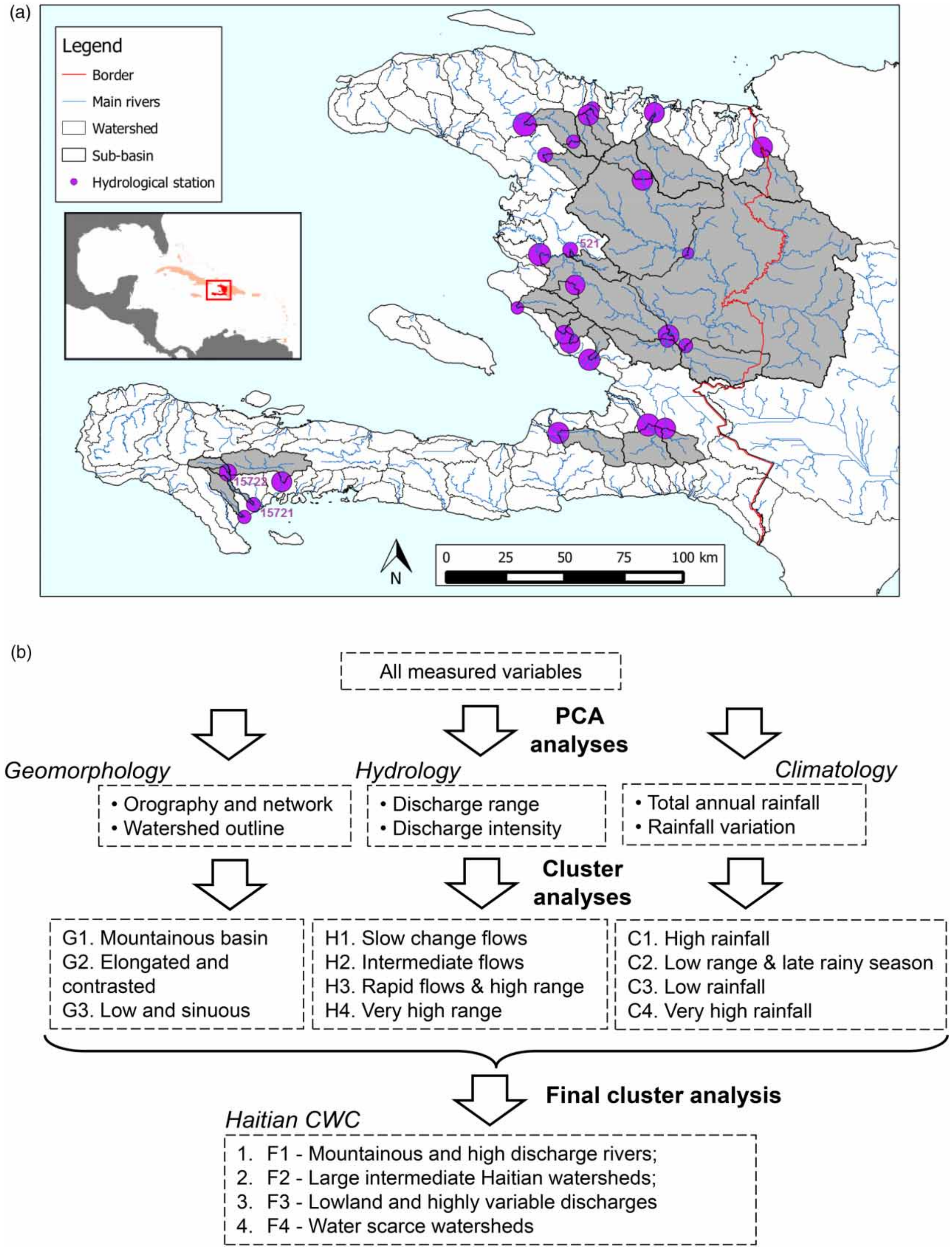

Figure 1 | Map of the Haitian data used in this study (a), with the flowchart indicating how they were combined (b). The river network and the associated watershed boundaries are displayed with the international border with the Dominican Republic and the coast of Haiti. Watersheds characterized in this study (26, covering 43% of the country) are displayed in grey with their associated hydrological station (circles, with a size proportional to the length of the available time series used). River outlier identifiers are displayed too. The flowchart (b) summarizes the three main stages of the statistical analysis of this paper: starting with PCA dedicated to each discipline and several variables (Table 1), the cluster analyses provided some groups ultimately gathered into final groups with integrated properties of the water cycle.

trade-related rainfall pattern) certainly blurs an unambiguous topographic signal beyond a weak-to-moderate windward/leeward effect versus the NE (and secondary SE) trades.

Data

To investigate the relationships between geomorphology, hydrology, and climatology in this country, we collected all available data at the same places (watersheds) and same dates (years) when possible at daily resolution (Figure 1(b)). Consequently, the spatial unit of the analysis here is the sub-watershed (or sub-basin) corresponding to the upstream area of available hydrometric stations. Some of the variables are fixed while hydrological and climatic variables refer to mean variations across the annual cycle. Further, to individually identify each watershed in the statistical analysis it is not necessary to understand their averaged behaviors (Figure 1(a)). This study is based on diversified watershed data, among which hydrological data represent the main limitation. The (sub-) watershed boundaries and river networks were computed using the ASTER GDEM v2 obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer in 2011, and the available river network of Haiti was digitized by the Centre National de l'Information Géo-Spatiale (CNIGS) in Haiti on the basis of a 1:50,000 scale topographic map (Polidori *et al.* 2014). Several other variables were derived from the ASTER GDEM to characterize the orography of the sub-watersheds (Table 1). We also quantified the main land cover (SlowLC, the only human-related variable in this study), geological, watershed outline (Bonhomme *et al.* 2013), and stream properties (Gaucherel & Salomon 2014) (Table 1).

The river discharges (flow rates) used in this study were collected by LGL (Lalonde, Girouard & Letendre – Canadian consultants), other private experts, and also from the public Haitian services (Table 1). The data concerned the 1919–1943 period and included 26 daily time series of (sub-)watersheds with at least five complete (no missing days, not necessarily the same dates between watersheds) years and 17 watersheds covering 43% of the country surface (Bonhomme *et al.* 2013; Polidori *et al.* 2014). From river discharges, we derived numerous hydrological indices to characterize stream flow regimes (Olden & Poff 2003). Several geomorphological variables were also derived from the DEM (Table 1). Finally, the rainfall data used in this study were derived from a rich dataset compiled from various sources of 78 daily rain gauges covering the 1905–2005 period (Moron *et al.* 2015). Considering the high interannual variability of rainfall, we decided to divide each year into four seasons (the dry season in December to March, the first rainy season in April to June, July alone, as is typical of the annual 'mid-summer' drought in Haiti (Moron *et al.* 2015), and the second rainy season in August to November). We then computed the average amount of rain received on (the rain gauges included in) the (sub-)watersheds during these four seasons (Table 1). We used these four variables (seasons) and mean annual rainfall to classify the 26 (sub-)watersheds of the study.

This study was clearly limited by the data available in such an understudied country. For example, detailed lithospheric and anthropogenic data were unavailable. Moreover, the measurements used were biased in terms of spatial coverage of this heterogeneous country (Polidori *et al.* 2014). No hydrological station covered the relatively dry north-west region, while only two stations were present in the north climatic region, which has a large late second rainy season. Similarly, there is a temporal bias in hydrological data as the years around the 1930s were quite wet (6% more) compared to the rest of the 20th century (Moron *et al.* 2015; Gaucherel *et al.* 2016). Yet, this bias is not significant (T-test p-value $= 0.11$) and only six of 78 stations are significantly different (p-value $= 0.01$) between both periods and were not located in a specific area of the country. In addition, our methodology is easily reproducible and the data used here will serve to further discuss the CWC. Additional data in the future will contribute to refine our current understanding of the CWC. Detailed data quality controls have been performed on each dataset, with poor quality data systematically cleaned (see next section), while no missing data have been supplemented to avoid increasing uncertainties. Finally, it is important to mention here that geomorphological observations were considered stable (static) for the whole study, whereas hydrology and climatology were considered dynamic (based on the daily or monthly time series). Indeed, it will be crucial during the discussion to recall that processes involved in the various components of Haitian watersheds do not cover the

Table 1 | List and descriptions of variables used in this study, with references mentioned when linked to Haitian analyses

Name	Description
Geomorphological variables	
SlopeM	Mean of the watershed slopes (extracted from ASTER GDEM v2)
Gravelius	This index refers to the watershed shape: values range from low values (around 1) for round watersheds to high values (around 3) for elongated watersheds
StreamDens	Cumulated length (in pixels) covered by the stream network divided by the watershed area (Gaucherel *et al.* 2017)
LengthContrast	Index of the statistical distribution of stream lengths over all Strahler orders. Values range from 0 (no difference) to 1 for the highest contrast between low and high order stream lengths computed on the loglog curve regression
FractDim	Average of the fractal dimension of watershed stream lengths weighted (i.e. normalized) by the stream lengths (Gaucherel & Salomon 2014)
BifurContrast	Index of bifurcations of a stream network based on Strahler orders. Values ranges from −1 and −2, for numerous bifurcations (more low order streams than high order streams) (Gaucherel & Salomon 2014)
SlowLC	Percentage of the watershed surface covered by land cover (forest, dense cropland) slowing down the runoffs
Basalt	Percentage of landforms composed of basaltic rocks, impermeable to infiltration flows (Gaucherel *et al.* 2017)
Hydrological variables	
FlowMed	Median of the daily flow discharge (runoff) of the watershed
FlowCV	Coefficient of variation of the daily discharge
FlowDer2	Average of the second derivative of the discharge (Gaucherel *et al.* 2016)
BFI	The low flow index is the ratio between the average of the seven lowest values of the year and the annual average of the discharge
HFD	The high flow index is the ratio between the average of the seven highest values of the year and the annual average of the discharge
FlowLowFreq	Frequency (number of days) of low discharge exceeding a 5% threshold of the median discharge
FlowChg	Annual average of the number of (day by day) discharge changes
Climatic variables	
RainM	Annual rainfall average per sub-watershed
RainStd	Standard deviation of the annual rainfall per sub-watershed
RainRg	Difference in rainfall between the wettest and the driest location of the sub-watershed
DJFM	Average of rainfall per sub-watershed in December, January, February, and March (dry season)
AMJ	Average of rainfall per sub-watershed in April, May, June (first rainy season)
Jl	Average of rainfall per sub-watershed in July (mid-summer drought) (Moron *et al.* 2015)
ASON	Average of rainfall per sub-watershed in August, September, October, and December (second rainy season)

same extent in space and time: they involve different scales (Huntington 2006; Koutsoyiannis 2013).

Methods

On the basis of the available data for the 26 sub-watersheds, we proceeded in two successive stages: (i) by characterizing and simplifying the various components of the CWC in Haiti; and (ii) then, comparing these characterizations with a simple yet robust statistical analysis. The reader will find details of the first stage in the respective papers of the project (Bonhomme *et al.* 2013; Polidori *et al.* 2014; Moron *et al.* 2015; Gaucherel *et al.* 2016), as only the overall results will be listed here. A drastic synthesis of (uncorrelated) variables was then successively made for each component of the CWC, leading to the most relevant variables (Figure 1(b)). On the basis of a multivariate analysis (here, a principal component analysis (PCA) (Pearson 1901)), we selected eight geomorphological, seven hydrological, and seven climatic variables (Table 1). From this reduced set of variables, new PCAs were computed with the 26 watersheds as observations, and we checked that their main principal component (PC) had the same interpretations as those of the initial analyses (i.e. with all variables). From these new PCs, clusters were derived with a hierarchical clustering analysis based on the Ward's criterion which minimizes the variance within clusters at each step of the process (Defays 1977).

To look for relationships in the CWC, we then computed pairwise (geomorphology–hydrology, hydrology–climatology, geomorphology–climatology) comparisons on the basis of the three (or four) PCs. We finally used a (multidimensional) RV test to estimate the significance of these comparisons: this test is based on RV correlation coefficient, a multivariate generalization of the squared Pearson correlation coefficient that measures the correlation between two sets of variables defined for the same watersheds (Heo & Gabriel 1997). Random permutations of watersheds using Monte Carlo computations define a null model to test the null-hypothesis that 'there is no relationship between components' (p-values lower than 0.05 will lead to an RV coefficient significantly different from a random relationship). We then checked that the RV permutation test, run over the original variables used in PCA instead of PCs themselves, systematically resulted in component differences with lower significance (i.e. higher p-value).

Ultimately, we computed a final classification on the basis of the previous property-wise groups to build an integrated picture of the CWC in Haiti. We supposed these groups to be fixed and we computed a dissimilarity matrix between them (Gower & Legendre 1986), with a matching distance based on the membership of watersheds in the different clusters: we increased the counter by one each time two watersheds were in the same property-wise group (0 otherwise). We then applied a hierarchical clustering analysis based on Ward's criterion to this dissimilarity matrix, in order to rigorously identify the dominant groups of our sample (Wishart 1969). This last stage enabled us to group Haitian watersheds on the basis of their geomorphological, hydrological, and climatological properties, and thus coherent behavior in terms of the integrated CWC studied (Huntington 2006; Moors & Stoffel 2013). Considering the small number of (sub-)watersheds in our sample (26), we built in parallel 'integrated' groups based on a fuzzy classification. Although it is always possible to build some groups using a statistical method, the final classification based on fuzzy groups was much more difficult to interpret (not shown) and seemed to discriminate geographical (e.g. north and south) properties rather than water-related properties as expected.

RESULTS

Characterization of CWC components

The geomorphological characterization of the 26 sub-watersheds of Haiti based on three PCs resulted in three clusters with clear differences in terms of the orography and morphometry of the stream networks (Figure 2(a)). The variance distribution of the PCA decreased sharply with 66% (respectively 80%) of the total variance obtained from the two (respectively three) main PCs. PC#1 is related to the orography and the pattern of stream network (i.e. how the stream network fills the watershed area). Dendritic networks in mountainous watersheds (i.e. numerous short and straight streams close to sources, negative PC#1 values) are opposed to watersheds with remarkable lowland areas and sinuous high (Strahler) order streams (positive PC#1 values). PC#2 mainly captures the outline shape of the watershed linked with the variation in length per stream order. Contrasting stream lengths per order are found in watersheds with an elongated shape (PC#2 negative values), and with a reduced coverage of basaltic rocks. The hierarchical clustering identified three clusters:

- Geomorphogical group G1 (10 watersheds) – mountainous watersheds with dendritic networks;
- G2 (6 watersheds) – elongated watersheds with highly contrasted (lowland/highland) lengths;
- G3 (10 watersheds) – sinuous stream networks in lowland watersheds.

The hydrological characterization of the 26 sub-watersheds of Haiti based on three PCs resulted in four clusters with different discharge rates (Figure 2(b)). The variance distribution of the PCA decreased sharply with 63% (respectively 81%) of the total variance obtained from the

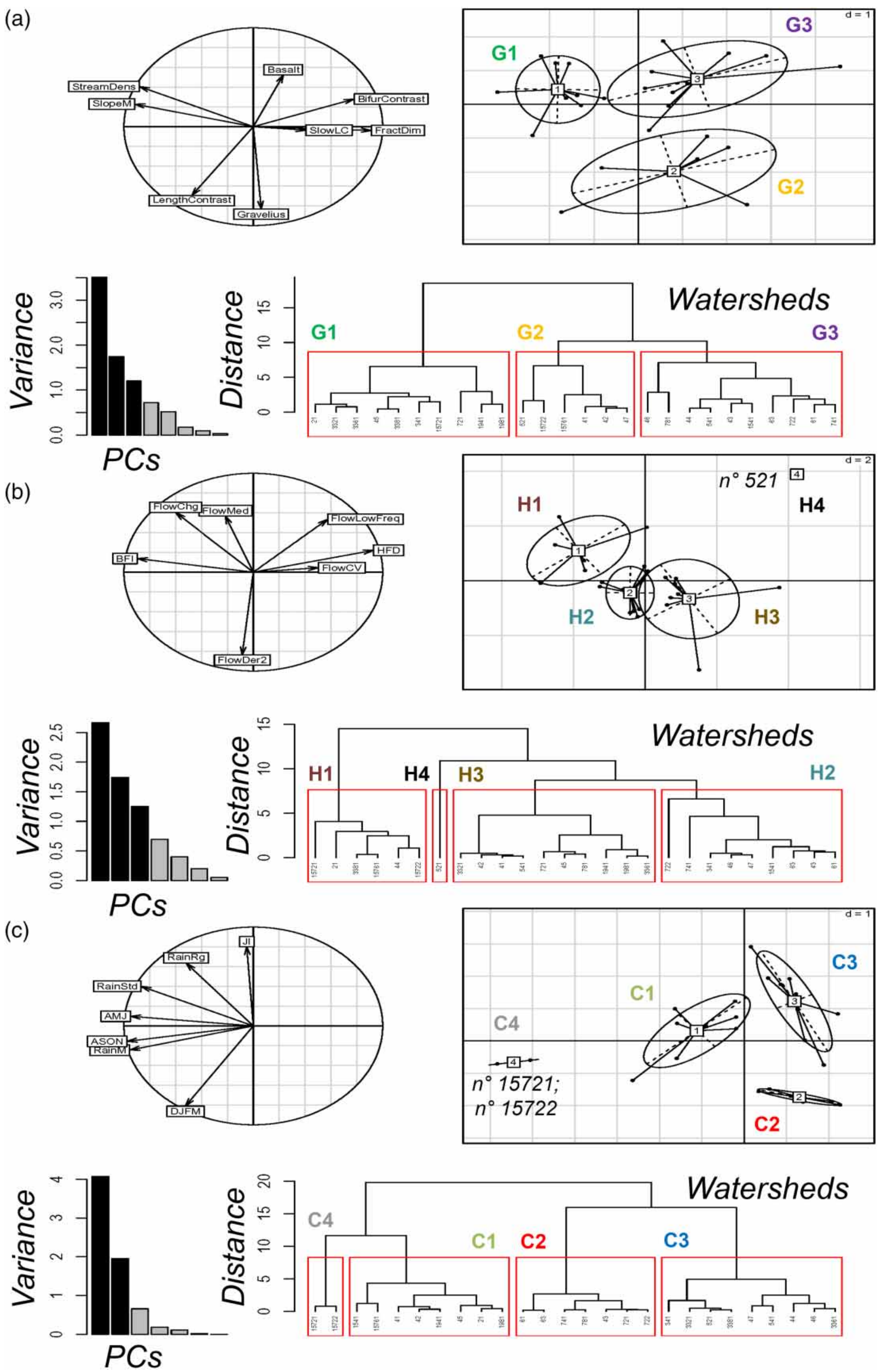

Figure 2 | The principal component analyses (PCA) of the successive water-related properties; geomorphology (a), hydrology (b), and climatology (c). For each of them, PC1 (x-axis) and PC2 (y-axis) plan on top (left – with variables, right – with watersheds), the associated eigenvalue variance distribution (bottom left, in bold the principal components), and each cluster dendrogram (bottom right) of the dedicated cluster analyses is displayed. Here, the variable distributions in PCA plans are more informative than variable names. River outlier identifiers are displayed too. Similarly, the watershed identifiers are not readable, as they are not relevant in themselves, rather than their clustering and well-separated group distributions (three, four, and four groups, respectively) in PCA plans.

two (respectively three) main PCs. PC#1 is related to the range of the discharge. The magnitude and duration of high flow indexes (HDF, positive values) are opposed to base flow indices (BFI). In terms of frequency, high numbers of low (labeled Flow) and high (Fhigh) flow rates both occur for high range discharges (positive values). PC#2 captures the intensity of the flow discharge. The median discharge value is opposed to the mean of the flow acceleration. Similarly, flows with high median values, a relatively high number of reversals but slow changes (positive values) are opposed to flows with rapid changes and with relatively low median and minimum values. The hierarchical clustering identified four clusters:

- Hydrological group H1 (six watersheds) – low discharge ranges with high median value of flow, relatively high number of reversals but slow changes;
- H2 (10 sub-watersheds) – intermediate Haitian watersheds in terms of discharge;
- H3 (nine watersheds) – high discharge ranges with rapid changes and with a relatively low median;
- H4 (one watershed, no. 521, Estere river) – an outlier having a very high discharge range and the sole river of our sample with null discharge in dry season.

The climatological characterization of the 26 sub-watersheds of Haiti based on two PCs resulted in four clusters with differences in annual rainfall and seasonality (Figure 2(c)). The variance distribution of the PCA provided 86% of the total variance obtained from the two main PCs. PC#1 is related to the total amount of annual rainfall received by the sub-watershed. Wet watersheds (positive values) are opposed to dry watersheds. PC#2 captures the variation in rainfall over the sub-watershed (range) and per season (dry as opposed to wet seasons). The hierarchical clustering identified four clusters:

- Climatological group C1 (eight watersheds) – high annual rainfall;
- C2 (seven watersheds) – low seasonal range, with a northern climate (late rainy season, pronounced mean summer drought);
- C3 (nine watersheds) – low annual rainfall;
- C4 (two watersheds, highly mountainous watersheds) – with very high rainfall averages.

We checked whether removing the annual rainfall average variable from the variable set led to the same classification.

Pairwise comparisons and component relationships

RV tests run for pairwise comparisons between CWC components showed few relationships between them alone. A significant relationship between geomorphology and climatology only was observed (RV p-value = 0.002). Although this relationship appears quite trivial, it was necessary to verify it in Haiti as it may have been wrong due to orographic and/or anthropogenic effects. Watersheds with dendritic stream patterns in mountainous areas (i.e. numerous short and straight streams close to sources, negative PC#1 and PC#2 values) received a higher total amount of annual rainfall (Figure 3(1c) and 3(3a). Conversely, watersheds with important lowland areas and sinuous high order streams receive less rain. This relation is likely contingent, as it seems that some watershed properties were highly dependent on geography. A weak yet significant correlation (p-value = 0.05) has also been found between hydrology and climatology (variables). It associates rivers with a high BFI (i.e. the river discharge range is low in the dry season) with watersheds receiving high rainfall amounts (Figure 3). No systematic relationship was observed for geomorphology versus hydrology (RV p-value = 0.3). Two more subtle and non-systematic relationships were also detected by a co-inertia analysis (Figure 3):

- intermediate river discharges (H2) often appeared correlated to mountainous watersheds with dendritic networks (G1), and to high annual rainfall (C1): six and five watersheds, respectively;
- low elevation and sinuous watersheds (G3) were often linked to rapid and high range discharges (H3) and to low rainfall ranges and late rainy seasons (C2): seven and six watersheds, respectively.

Because some property relationships were occasionally detected (i.e. for some watersheds only), it was relevant to compute a final classification simultaneously taking into account all available CWC properties. Based on a dissimilarity matrix and a hierarchical clustering, we rigorously identified four groups of watersheds (Figure 4(a)), and

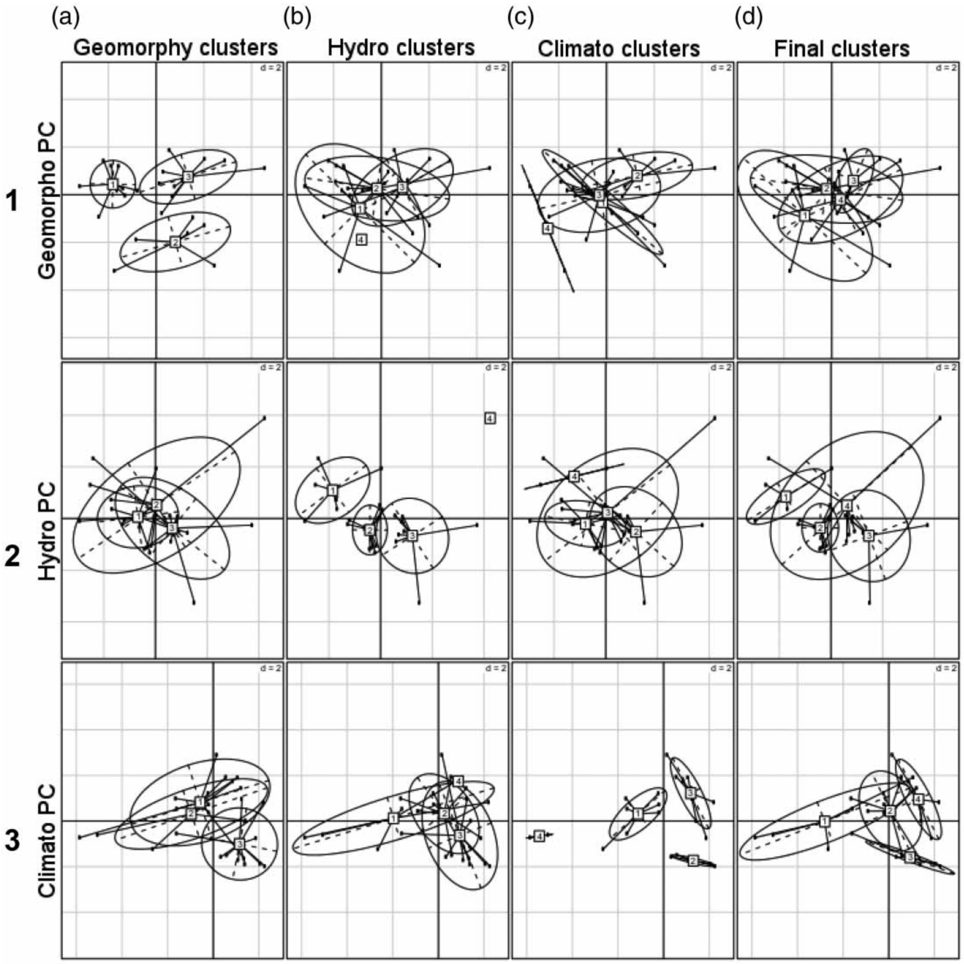

Figure 3 | Graphical comparison of multivariate analysis and typologies at different scales. Columns show clusters identified for the different water cycle components, respectively (a) geomorphology, (b) hydrology, (c) climatology, and (d) final classification. Rows show the same clusters projected into the first two principal components (PC1: x-axis, PC2: y-axis) computed for (1) geomorphology, (2) hydrology, and (3) climatology variables. The diagonal (a1, b2, and c3) shows the same clusters in their respective PC space (similar to Figure 2). The other plans highlight the relationships between the different components. Ellipses display the 95% confidence levels of each cluster. Notice that the group distributions in PCA plans (ellipses) are well separated for each science (along the diagonal), but not between different sciences (off-diagonal).

found the two above-mentioned groups. The final group F1 (five watersheds) showed mountainous and high discharge rivers, and was equivalent to group H1 (and the two outliers C4) showing low discharge ranges with high median value of flow, a relatively high number of reversals, but slow changes and high annual rainfall (Table 2). These watersheds are small (96 km^2), their stream network is dense (0.79 m^{-1}) and quite rectilinear (low fractal dimension of lengths), carrying a relatively constant amount of water (high BFI $= 0.4$) of a median discharge equal to 1.5 $Ls^{-1}\,km^{-2}$. The final group F2 (nine watersheds), large intermediate Haitian watersheds, was equivalent to the former (a) correlated group H2-G1-C1, and showed larger-than-average watersheds (275 km^2) with high elevation sources and extended lowlands, resulting in intermediate river discharges and intermediate geomorphology and climate.

The final group F3 (six watersheds), rivers in lowland with highly variable discharge – a highly homogeneous group in terms of watershed behaviors – was equivalent to the latter (b) correlated group G3-H3-C2, and showed a low elevation on average (437 m), a high range of discharge (high BFI $= 9.5$, low HFD $= 0.11$), and low range of annual rainfall (late rainy season and relatively lower rainy season). They have a low compactness Gravelius coefficient (2.1) indicating elongated watersheds, sinuous lowland streams, with 90% of land cover slowing down the runoffs

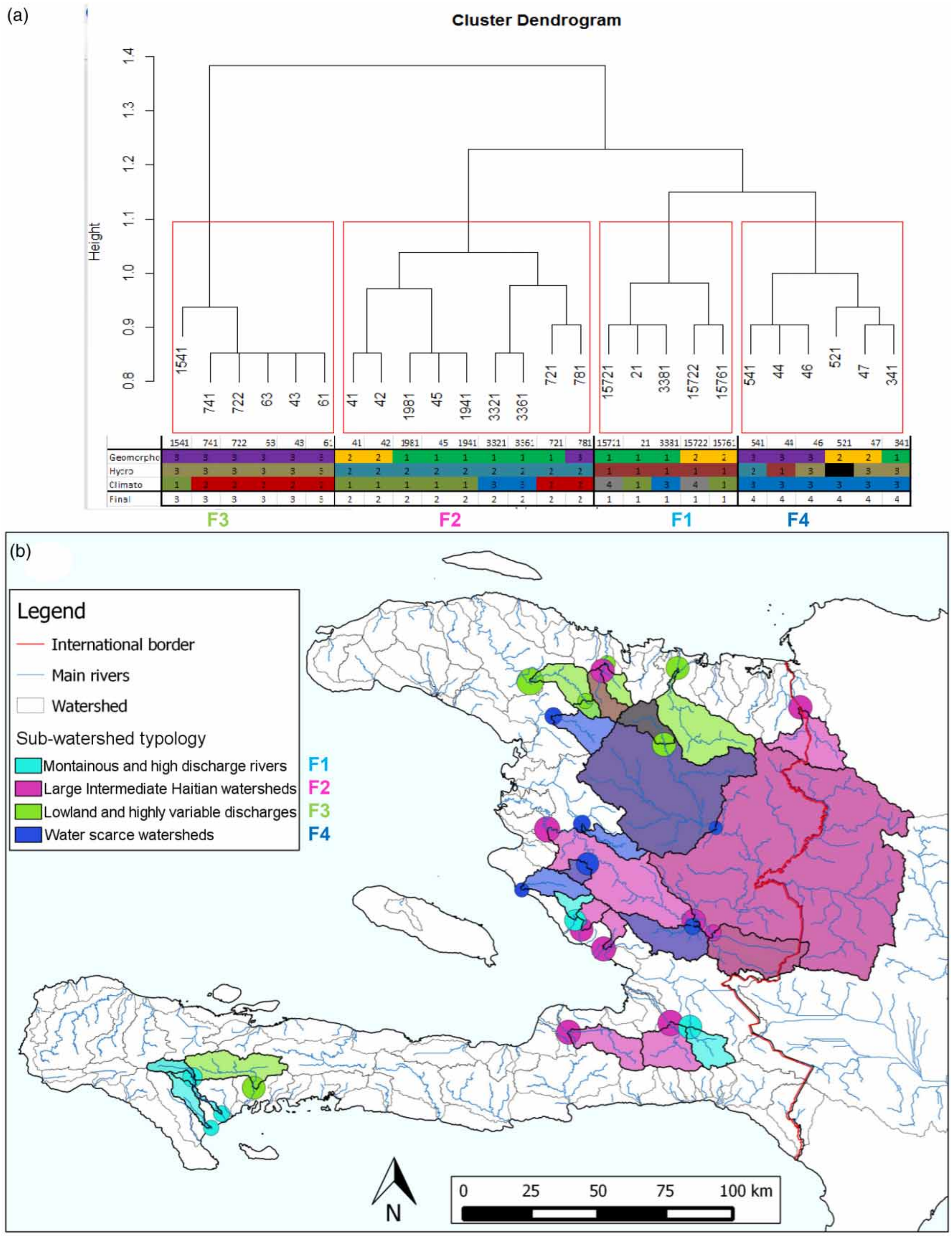

Figure 4 | Final classification (a) and map (b) of the groups identified in Haiti and combining all the studied properties. Below the hierarchical classification (a) are found the various groups of sub-watersheds (their numbers in lines) with specific shades. Final groups mapped (b) are: F1 – mountainous and high discharge rivers; F2 – large intermediate Haitian watersheds; F3 – lowland and highly variable discharges; F4 – water-scarce watersheds. The 26 hydrological stations, for which the circle size is proportional to the length of available time series discharge, are located on the simplified river network with the main watershed limits.

Table 2 | Median values for groups of the final classification (see Figure 4(a))

	Mountainous and high discharge rivers (F1)	Large intermediate Haitian watersheds (F2)	Lowland and highly variable discharges (F3)	Water-scarce watersheds (F4)	Total
Total area (km^2)	96	275	234	180	185
Mean altitude (m)	1,046	741	437	509	573
Drainage density (km^{-1})	0.79	0.74	0.68	0.66	0.69
Mean slope	44.1	37.4	31.2	32.7	33.8
Median flow (Ls^{-1} km^{-2})	1.50	1.00	1.15	0.75	1.05
HFD	4.20	4.40	9.50	8.41	6.92
BFI	0.41	0.21	0.11	0.14	0.19
Annual rainfall (mm)	1,986	1,592	1,578	1,476	1,555
Total rainfall in dry season DJFM (mm)	90.6	46.7	78.5	33.3	51.0
Total rainfall in wet season AMJ (mm)	205.5	182.7	155.0	163.9	172.4
Gravelius index	2.39	2.27	2.11	2.31	2.30
Slow runoff land cover percentage	59	64	91	44	65
Number of concerned (sub-) watersheds	5	9	6	6	26

(Table 2). The final group F4 (six watersheds), water-scarce watershed, was equivalent to the group C3 with the lowest annual rainfall (1,476 mm), the lowest median discharge (0.75 Ls^{-1} km^{-2}), the lowest proportion of land cover slowing down water runoff (44%), and is mainly located inland (Artibonite and La Quinte basins, not shown). Although some geographical patterns emerged from this final classification (e.g. F3 is mainly located in the northern plain with a specific climate), most of the groups appeared to be relatively spread out across the country (Figure 4(b)).

DISCUSSION

Water component relationships

The BVH project was a success in that it greatly increased the knowledge of regional water resources in Haiti. The study has provided an original and almost exhaustive characterization of watersheds, encompassing their main properties such as geomorphology (Gaucherel *et al.* 2017), including topography (Bonhomme *et al.* 2013; Polidori *et al.* 2014), hydrology (Gaucherel *et al.* 2016), and climatology (Moron *et al.* 2015). The data are still far from optimal (short time series, biased spatial coverage, etc.), but they constitute a preliminary and unprecedented effort to quantify the water resources in such an understudied country and the (superficial) part of the CWC of this region. The study has shown that it is relevant to systematically identify three to four groups of watersheds according to their quantitative properties: watersheds were mountainous, elongated and contrasted or at low elevation; river discharge variations were slow, intermediate or rapid with high ranges; while rainfall regimes were high, low or low with a late rainy season (Figures 1(b) and 2).

Surprisingly, despite large variations for all variables, our statistical analysis did not lead to any relevant and significant relationships (RV correlations) between annual rainfall/river network/watershed morphology/runoff, thus confirming that the CWC is made of partly independent components and/or highly non-linear processes. Hence, an integrated view of such regional water cycle appears difficult to grasp and mandatory to have, as observed elsewhere (Huntington 2006; Hrachowitz *et al.* 2013; Montanari *et al.* 2013). Despite the low number of watersheds, the statistical analysis used here was simple and robust. Indeed, variables were selected based on a wide range of factors, based on a careful cleaning stage, and dependent neither on the selected variables nor on the clustering method used (k-means led to the same qualitative results as the hierarchical clustering). Moreover, several variables used in this study were also sensitive to (data and measurement) scales, but were computed at the same scale in order to further compare the watersheds. All these precautions do not preclude that the lack of correlations found in this study partly comes from the limited amount of available data. Our methodology is therefore robust and reproducible.

On a more fundamental view, we found no systematic pairwise relationships between the studied CWC components but the relationship between the geomorphological and climatological components (RV test p-value = 0.002). We hypothesize that this intriguing relationship may be due to the broad time scales of these two components (geomorphology and climate, contrary to hydrology) are interacting (Moron *et al.* 2015). The final comparison of such contrasted measurements of CWC components also demonstrated some less systematic relationships. For example, we observed that mountainous watersheds do not necessarily exhibit the higher and fastest river discharges (F2, Figures 3 and 4(a)) and that, surprisingly, low-elevation watersheds often demonstrate rapid discharge regimes (F3). This could not have been predicted from the literature and the common background in water sciences (Dooge 1986; Olden & Poff 2003), and is certainly a contingent feature in Haiti (CEGET 1985). The weak correlation between annual rainfall mean intensity and NE aspects due to the interaction between topography and usual trade regimes has been found, but the absence of any systematic relationship between mean rainfall and elevation reflects the complex geography of the island and the multiplicity of rain-bearing systems. A combination of many factors may be involved here to blur any clear-cut relationship, among which the frequent occurrence of cyclones, the Dominican Republic partly shading the Haitian country vs. trade winds, and the complex country shape (e.g. the southern tip). For these reasons, it would be relevant to compare Haiti and the neighboring Dominican Republic to quantify these effects as well as effects of topography and vegetation on erosion, on hydrology, and finally on the CWC.

Several reasons can explain the lack of significant relationships among the CWC components. First, water gets infiltrated and stored in the water table, and our study clearly lacked underground measurements and characterizations. One of our early assumptions was that hydrological watersheds were considered equivalent to topographical watersheds. We therefore discussed the 'superficial' (i.e. aerial, surface, and sub-surface) characterizations of watersheds of the CWC only. Infiltration and evaporation processes, assumed to be uniform in the country (Moron *et al.* 2015), were lacking in our study too. Geology, and in particular the extended karsts covering Haiti, may likely impact infiltration and thus explain part of the poor relationships found here, while the Haitian orography may likely modulate evaporation.

In addition, we likely underestimated the human factor in this CWC system. Land cover was also taken into account in the morphological analysis (e.g. SlowLC index), but did not lead to any relevant, uncorrelated, and discriminant variable (Polidori *et al.* 2014; Gaucherel *et al.* 2017). The long-lasting deforestation and agricultural intensification in Haiti led to an almost uniform low-vegetation layer that justifies considering a uniform infiltration. Some limitations and errors due to the use of ASTER GDEM for index calculations must also be recalled: namely, the mesh size (30 m) and elevation quality that may propagate through the morphometric and hydrographical indices computed (El Hage *et al.* 2012). Datasets may also be noisy, so that they blur present correlations. Finally, it should be kept in mind that the runoff is the result of the rainfall regime, the watershed geomorphology, and the human controls in complex and nonlinear ways. We captured the CWC properties considering superficial flows only, as such flows are a key resource and are more easily measurable, especially in developing countries such as Haiti.

An integrated CWC

To integrate the CWC components into a coherent view, the statistical analysis helped to identify similar watersheds (gathered into the same final groups), suggesting a similar functioning and therefore a similar management in Haiti (Cudennec *et al.* 2015). Human health and environmental risks of the CWC are directly concerned too. For example, the watersheds of the final F1 group have sources at the highest elevations of the country (massif de la Hotte, Chaine de la Selle, and Chaine des matheux) (Figure 4(b)), and suggest constantly available ground waters (no strong dry season) and the availability of water for irrigation. Conversely, erosion could be a problem in these mountainous areas (high slopes and around 2 m of annual rainfall). The watersheds of the final F3 group are mainly located in the northern part of the country (Figure 4(b)). The water resource of their rapidly changing discharges should be carefully managed: while this area may be suitable for agriculture purposes, water is scarce, and the low rainfall range suggests rainfed agriculture and a reduction of irrigation use (Table 2). Extreme (floods and droughts) events could be a problem there. Similarly, as the final F4 group (Figure 4) has the lowest water resources, water harvesting technology should be encouraged there, and the use of water for industrial purposes carefully avoided.

We can now complete the picture of this complex system and of its study (Figure 5): every question starts from needs related to the CWC. While practical needs are related to agriculture, flood mitigation, human health, or water quality issues (Cincotta *et al.* 2000; Moors & Stoffel 2013), the fundamental needs require an answer to several questions linked, for example, to water resource availability and to the water cycle intensification (Allen & Ingram 2002; Huntington 2006). There is a clear practical need to improve our capacity to predict the water cycle and reduce the present-day uncertainties (Kennard *et al.* 2010; Hrachowitz *et al.* 2013). Simultaneously, there is a fundamental need to increase our understanding of this water-related environment (Figure 5, bottom). For example, while most water-related variables in the world seem to show a trend, possibly due to global warming, it is not clear how extreme events would behave in the future (Huntington 2006; Gaucherel & Moron 2016). Both suggestions need finer and more frequent monitoring wherever possible, and regionalization attempts in this context are welcome (Chiang *et al.* 2002; Wagener *et al.* 2007; Snelder *et al.* 2013). Simultaneously, various modeling schemes of any kind (statistical, empirical, mechanistic) have proven complementary efficiencies (Hrachowitz *et al.* 2013).

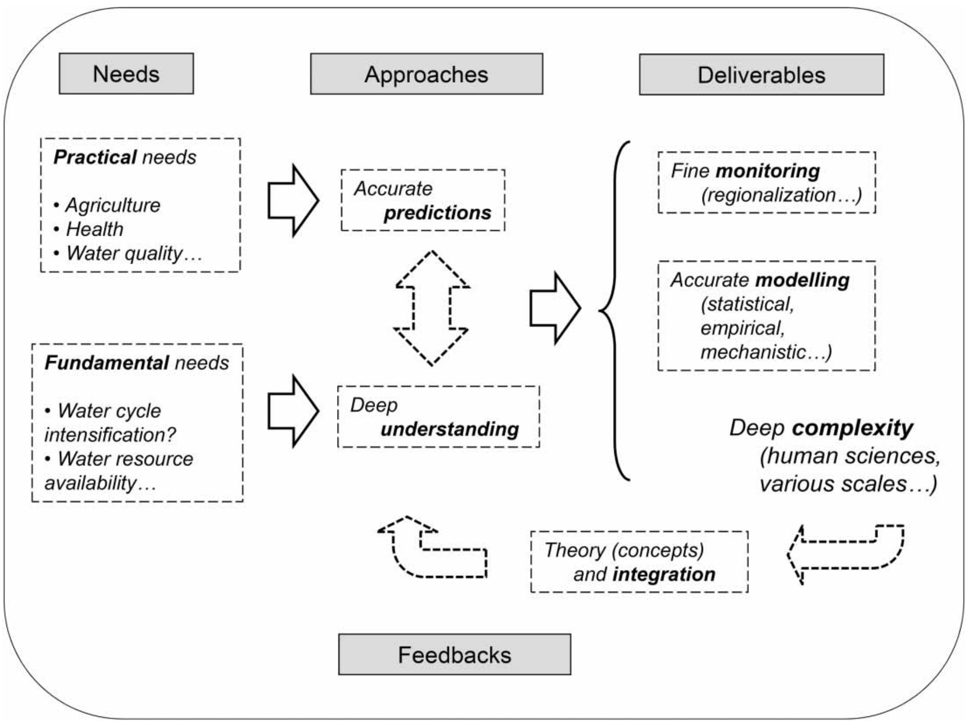

Figure 5 | Diagram summarizing the concept relationships handled in the paper discussion. Starting from the population needs concerning the water cycle, the scientific community developed several complementary approaches, leading to various deliverables to better understand and predict this cycle. Plain arrows represent the natural (obvious) flows of this process. The deep complexity of the water cycle forces us to a necessary theoretical reflection providing useful feedbacks on the previous approaches. Dashed arrows represent the useful interactions between stages involved in this process.

Yet, everywhere, we see how complex the water cycle is, partly due to the physical processes we explored in this study, partly to the social science processes too (Cincotta *et al.* 2000; Kriegler *et al.* 2009), and to the wide range of spatial and temporal scales involved in the system (Huntington 2006; Trenberth *et al.* 2007; Koutsoyiannis 2013; Gaucherel *et al.* 2016). There is an obvious need to define a range of adaptation strategies, built in deep collaboration between scientists and stakeholders on the basis of tested scenarios, such as made on landscape dynamics (Houet *et al.* 2010; Gaucherel *et al.* 2012). In addition to compulsory monitoring and modeling efforts, we argue here that it is crucial to simultaneously increase our theoretical efforts (Figure 5). We noticed that water sciences are still lacking some critical concepts that may help to grasp the system's complexity and integrate the large number of processes of various natures involved into this system (Huntington 2006; Moors & Stoffel 2013; Gaucherel & Salomon 2014). Feedback from theoretical efforts would be of benefit to the whole field, in turn feeding the previous approaches explored, as well as helping to redefine needs, in a virtuous cycle (Figure 5). To draw such a unified view of the CWC is a huge program, but it would benefit water sciences in their diversity as well as for developing country managements (Boyer *et al.* 2011; Shamir *et al.* 2013).

CONCLUSION

In this study, we looked for connections among the atmosphere, hydrosphere, and geosphere components involved in the CWC in a specific understudied region (Haiti). Our objective was to improve the understanding on the overall CWC to ultimately provide Haiti with a milestone referential for improving its ecological management. Surprisingly, no clear relationships but the geomorphology–climatology one have been detected, thus confirming complex and non-linear interactions in the water cycle.

Considering some of the above-mentioned contingent relationships (Figures 3 and 4(a)), we cannot assume that Haiti is sufficiently representative of any CWC to infer generic knowledge on it. Yet, the rigorous statistical analysis presented here is a preliminary step to most explorations of the water cycle and to an integrated view of the water-related environment. To gain explicative power in the water cycle dynamics, we have no choice but to develop more theoretical (i.e. conceptual) models of the CWC (Figure 5). In parallel, to gain predictive power in water-related environmental health, we have no choice but to develop applied and more mechanistic models at various scales, regularly fed by new collected data. Both objectives are complementary and should be targeted simultaneously.

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