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# Mass balance of nitrogen and potassium in urban groundwater in Central Africa, Yaounde/Cameroon

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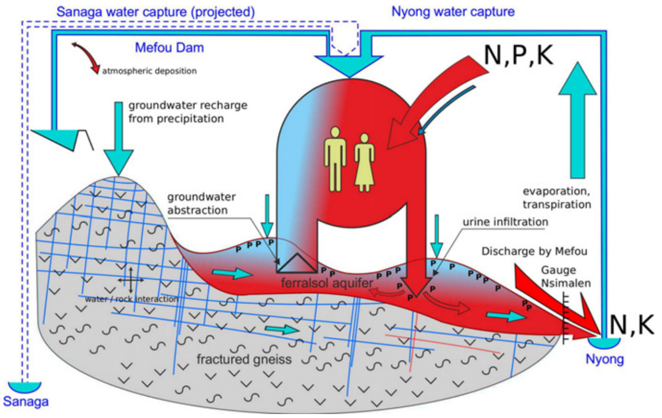
## HIGHLIGHTS

- Predicting TIN by EC measurement in urban groundwater in a ferralsol aquifer
- Anthropogenic groundwater types dominated by $NO_3^-$, $NH_4^+$ and urine related salts
- Incomplete nitrification under acidic pH conditions
- Indirect evidence for very little denitrification
- Nutrient turnover (TIN & K) is very high compared to national fertilizer imports.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Mass flow of nutrients from innumerous latrines and septic tanks was assessed to best describe the groundwater quality situation in the urban environment of Yaounde. 37 groundwater samples were taken at the end of dry season 2012 and analysed for nutrient related ($NO_3^-$, $NH_4^+$, $NO_2^-$, $K^+$, $Cl^-$, $HPO_4^{2-}$ and TOC) and physico-chemical ambient parameters. A survey on waste water discharge close to water points constrained point sources from sanitation. The results showed that the median of nitrate concentration exceeds the WHO limit. We realized that EC increases from the geogenic background to very high levels in the urban area within short distance, suggesting anthropogenic input. Dug wells showed nitrate and ammonium in equivalent concentrations, indicating incomplete nitrification and mandating their inclusion into water type classification. The mass turnover of nutrients in urban groundwater scales high in comparison to national statistical figures on fertilizer import for 2012. A mass N,K balance for infiltration water overestimates observed concentrations by a factor of 4.5. The marked balance gap is attributed to dynamic non-equilibrium between input and output. Unresolved questions like a) urban sanitation, b) hygiene & health and c) environmental protection urgently call for closing the nutrient cycle. In the light of Cameroonian strategies on rural development, tackling the groundwater nutrient, urban agriculture, food

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— NEXUS might partially restore urban and periurban ecosystem services under economical constraints and thus improve living conditions.

## 1. Introduction

### 1.1. Nitrogen in groundwater under the nutrient aspects

Groundwater is an indispensable resource to sustain livelihoods in situations where the extension of public water supply does not keep up with unregulated urbanization fuelled by population growth and internal migration (Tanawa et al., 2003; Enimelie Ndiomo et al., 2005; Ngnikam et al., 2007). Be it for a long term underfunding of the subsector, difficult hydrological conditions or a combination thereof (Water and Sanitation Program — Africa Region, 2013), insufficient piped water supply forces populations to rely on the local groundwater reserves for survival (Bemmo et al., 1998; Kuitcha et al., 2008; Fouépé Takounjou et al., 2013). The proximity to ubiquitous contamination sources from housing, craft-shops and small industry, combined with the absence or integrity of protective layers, puts these groundwater resources at special risk. Additionally, the risk for contamination is increased through the nearly complete absence of functioning centralized or semi-centralized sanitation systems (Bemmo et al., 1998; Wethé et al., 2003; Water and Sanitation Program — Africa Region, 2013).

Agriculture lies at the heart of all population-rich human cultures. To date 1.5 times the preindustrial background of global reactive nitrogen is added by human activity (UNESCO and SCOPE, 2007). Fertilizer application exceeding plant uptake and removal by harvest has brought with it a large N-export with world rivers (Caraco and Cole, 1999), causing eutrophication of coastal seas and freshwater reservoirs (Smith et al., 1999) as well as damaging groundwater reservoirs (Angle et al., 1989; Spalding and Exner, 1993; Puckett et al., 2011). These unwanted consequences have largely affected river basins with a high population density (van Egmond et al., 2002; Rivett et al., 2008). N-export in its prevailing form, dissolved nitrate anions, reversibly adsorb with Fe(III)Al-rich soil particles (Cahn et al., 1992) and are moderately retarded by the aquifer matrix (Duwig et al., 2003). Transport occurs slower than the mean velocity of groundwater in the environment.

Groundwater and seepage in tropical West-Africa generally has a low electrical conductivity (EC) ranging from 10 μS/cm to 200 μS/cm due to a persistent seasonal dilution effect (Roose and Lelong, 1981). Ohou et al. (2008) monitored nitrate concentrations of shallow dug wells ("dug well's" hereafter) in Ivory Coast for one hydrological year and showed that a majority of water points in villages and a town exceeded the WHO nitrate limit. They identified the proximity of pit latrines to wells and the individual setting (e.g. depth) as the most important factors affecting nitrate concentrations. The impact of urine, excreta and waste water on groundwater quality has been investigated in a number of studies (Wolf, 2006; Rose et al., 2015 and Graham and Polizzotto, 2013). For groundwater in coastal, rural Cameroon, Wotany et al. (2013) gave a comprehensive account of anthropogenic and geogenic factors on quality. For Yaounde, Bemmo et al. (1998) attributed groundwater quality to waste water input. Fouépé Takounjou et al. (2013) reviewed the state of knowledge on nitrate in urban groundwater in Cameroon, concluding that concentration levels exceeded the WHO (2004) limit in >50% of cases. Kuitcha et al. (2013) described a Na,K-Cl-type groundwater as a typical phenomenon for Yaounde, not regarding nitrogen compounds.

The *working hypothesis* of this paper is, that decentral sanitation is effectively controlling urban groundwater quality, leading to the formation of anthropogenic groundwater types, previously not reported for the sub-Saharan region. The degree of contamination with nitrogen and related parameters is discussed in the framework of geogenic background. The formation of groundwater quality is charted by sampling at distinct hydrological positions. The water points represent different socio-economic conditions from periurban over dense informal settlement to planned urban settlement. A rare insight into nitrogen speciation and transformation processes under ambient tropical conditions is given. Survey results on decentral sanitation help to constrain the nutrient load (N,K) to the urban aquifer. A *predicted* mean infiltration concentration from decentral sanitation is critically discussed in comparison to *observed* groundwater concentrations for total inorganic nitrogen.

### 1.2. Location and hydrogeological setting

Yaounde city is located within latitudes 3°50′ and 3°55′ N, and 11°27′ and 11°35′ E. The rapid growth of the Cameroonian capital is documented by a doubling from 1976 to 1987 and a tripling, reaching 1.8 mio. Inhabitants in 2005 (BUCREP, 2005). Tchindjang et al. (2009) charted the rapid expansion of the urban area. The population is expected to approach 2.5 million inhabitants at a growth rate of 5.7%/a (BUCREP, 2010 and pers. comm. Tsafack, 2015, BUCREP).

The relief in Yaounde is undulating terrain with differences between 20 and 40 m at an average altitude of 730 m.a.s.l. and seven prominent "inselberge" with steep slopes (see Fig. 1, Fig. 7) to the north-west which rise up to 1060 m.a.s.l. Annual average precipitation in Yaounde is 1600 mm and the mean annual temperature is 23 °C (Olivry, 1986; Sighomnou, 2004). The climate is equatorial with two rainy (mid-March to mid-June; mid-September to mid-November) and two dry seasons (mid-November to mid-March, mid-June to mid-September) (Suchel, 1988). Prevailing heavy rainfalls are drained by a set of perennial rivers (Mfoundi and Mefou to the south and Mfoulou to the north), causing inundations of the valley bottom.

The geology is made up of crystalline basement rocks such as paragneiss, migmatitic gneiss and schists of proterozooic age, metamorphosed in the panafrican orogeny at the northern margin of the Congo craton (Ball et al., 1984; Toteu et al., 2004; Mvondo et al., 2007). These medium to highgrade metasediments are deeply weathered to a lateritic soil profile (ferralsols) of up to 20 m thickness (Yongue-Fouateu, 1986; Kamgang and Ekodeck, 1994). The bedrock is covered by alluvial hydromorphic clay and sand in the valleys (Ngon Ngon et al., 2009) and ferralsols on the hillsides (Yongue-Fouateu, 1986). The hydrogeological setting is an unconfined porous aquifer on top of a fractured gneiss aquifer of much lower productivity as shown in Fig. 1. The seasonal dynamics of unconfined groundwater flow are given by Ntep et al. (2014), who reported mean groundwater level fluctuations of 0.49 m for the valleys, 0.65 m for slopes and 1.3 m for plateau positions between rainy season and dry season. Low yields of springs increased by a factor of 3 during rainy season. Fouépé Takounjou et al. (2009) stated that groundwater surfaces follows terrain generally well.

## 2. Methods

### 2.1. Sampling

A sampling campaign, preceded by a mapping of water points, was carried out to obtain an aspect of the groundwater quality from springs, dug wells and production wells in hydrologically and socio-economic different urban environments of Yaounde *at the end of the long dry season* April 2012. The water points were within or close to five *spatial clusters* of households chosen for a groundwater, sanitation and health survey (INS/BGR 2013) introduced in Fig. 3.

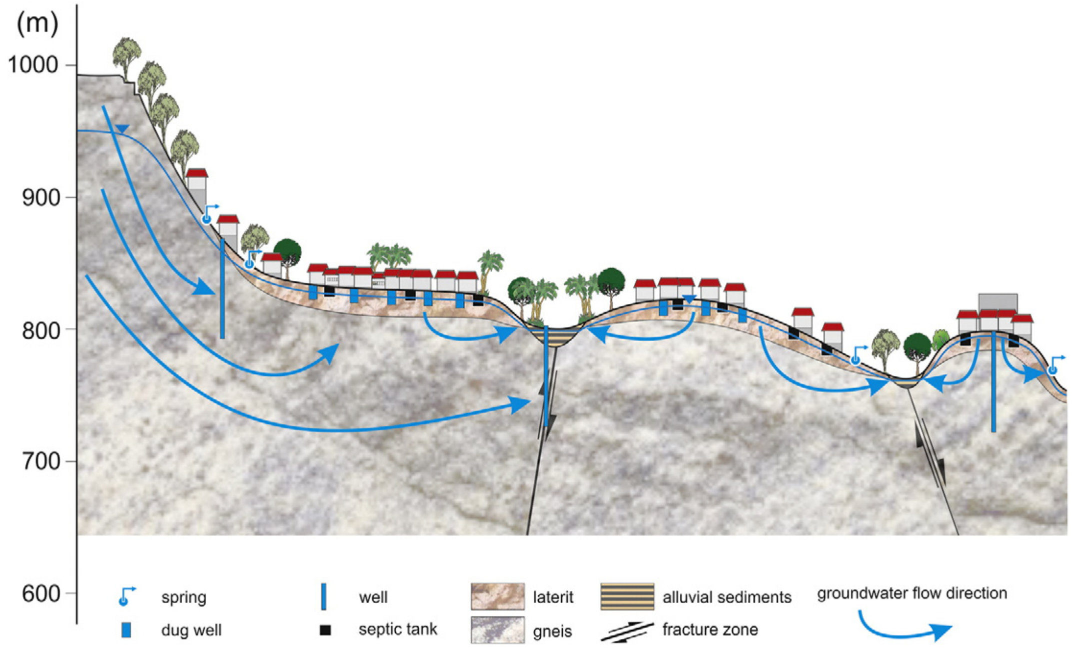

**Fig. 1.** Sketch of the hydrogeological arrangement of terrain, aquifers, drainage network of Yaounde in relation to urban settlement and decentralized installations of water supply and discharge; groundwater surface and flowlines only approximate — not to scale.

- Ekoudou (close to recharge, fringe of settlement),
- Messa Carrière (close to recharge, dense unplanned settlement, steep slopes),
- Madagascar (dense urban settlement, craftshops, flood prone),
- Ngoa Ekèlè (dense urban settlement, student dorms on isolated hill) and
- Biyem Assi/Obili (developed urban settlement).

37 groundwater samples (20 dug wells, 13 springs, 4 production wells) were taken during the campaign with 10 surface water samples for comparison.

Care was taken to sample the groundwater as it is used by the population to allow for microbiological sampling (Rechenburg et al., in prep). Standard well clearing procedures were thus not applied. Instead the local available water fetching equipment was used after thorough washing with sample water. After taking the microbiological samples, physicochemical properties (EC (±0.5%), pH (±0.05 pH), DO (±5%), ORP (±50 mV)) were determined in the field with an WTW Multimeter. The hydrochemical sampling set consisted of: 1) TIC/TOC (30 ml glass screw flask with Al-membrane, filled bubble-free), 2) cations and trace elements (100 mL PE bottle, prepared with 1 wt.% (1 mL) $HNO_{3ccsp}$, sample filtrated through 0.45 μm cellulose acetate membrane disposable filter after conditioning of syringe and filter and 3) anions and alkalinity (250 mL PE bottle, pre-rinsed with sample).

### 2.2. Analytical methods

Major elements were analysed in the laboratory of the Federal Institute for Geosciences and Natural Resources (BGR), Hanover/Germany. For the analysis of nitrate (±1.5%) and sulphate (±1.5%) an ion chromatograph ICS 3000 (Dionex) was used based on DIN EN ISO 10304-1 (1995). Anion peaks were detected by EC, following neutralization of the alkaline KOH-eluent with a membrane suppressor technique. Alkalinity (± 0.5%) was determined by automatically titrating a 25 mL aliquot of the unfiltrated sample with 0.02 N HCl to pH 3 using a TA10 plus, TWplus digital titration station (Schott) based on DIN 38 409, H7 (1979). Nitrite (±5%) was determined in a parallel sample spectrophotometrically by Centre Pasteur/Yaounde with a Spectroquant™ Merck-kit with a determination limit of <0.1 mg/l $NO_2$. Ammonium (±3%) was determined spectrophotometrically with a Unicam UV300 (Thermo Electron Corporation) with the blue indophenole reaction according to DIN 38 406, E5 (1983). Cations (± 1–2%) as well as chloride (±1.5%) and sulphate (as S) (±2%) were analysed via inductively coupled plasma optical emission spectrometry using a Ciros by Spectro, based on standard DIN EN ISO 11885 (1997). The total inorganic (±3%) and organic carbon (±10%, if <1 mg/l) was measured by infrared detection of $CO_2$ after catalytic combustion with a High TOC II (Elementar) according to DIN EN 1484 (1997).

### 2.3. Thematic mapping and data analysis

Field data (location, sample and analytical results as well as survey results) was treated as unprojected latitude, longitude data with WGS84 datum with an Open Source QGIS 2.8 client (QGIS Development Team, 2013), a PostgreSQL 9.2.x (Postgresql Global Development Group, 2013) database server with PostGIS (2.0.×) (PostGIS, Group of Contributors, and Steering Committee, 2013). Statistical and graphical analysis was done with R-Statistics 2.15 (R Core Team, 2012), ORIGIN™ (V. 8.6) and MA-software (Kringel and Bahr, 2011). OpenStreetmap *Open Data* (OpenStreetMap contributors 2012–2015, (licence: CC-BY-SA 2.0)) has been used as basemap, as has been the SRTM digital surface model (Farr et al., 2007) with 30 m resolution (Jet Propulsion Laboratory 2014) for thematic maps.

### 2.4. Groundwater, health and sanitation survey

A survey among 1134 households in the vicinity of groundwater points was realized (INS and BGR, 2013). A questionnaire was administered to the selected household heads or its representative and an individual questionnaire was administered to any person aged 15 and above in the household, on the knowledge, perception and attitudes towards the urban environment.

## 3. Results and discussion

### 3.1. Spatial distribution and correlation of nutrient related parameters

The range and univariate distribution of parameters related to the trophic status of groundwater is given in Fig. 2. Macro nutrients required for plant growth (NPK) and associated chloride are given as minimum, percentiles p10, p25, p50 (median value), p75, p90 and maximum. Distinction between natural springs and dug wells is made additionally in Table 1 in Appendix A. Background concentrations from soil water under forest (Braun et al., 2005) are given in Fig. 2 with the high range (NZ) representing concentrations in the weathering zone in the saprolite. Enrichment factors of 128 for chloride and 693 for nitrate result, when the geogenic background is related to the urban groundwater median (p50). The enrichment factor is only 100 for potassium and as low as 40 for sulphate. This is because the latter is released by weathering traces of primary sulphide mineral present in the metasediments and the former by weathering of biotite and K-feldspar (Ball et al., 1984). Total organic carbon (TOC) is taken as a robust estimate for dissolved organic carbon (DOC). The range of TOC under forest is slightly above the median of the urban environment, where no disintegrating plant-litter/humic horizon is present. It is far below the humic substance background of mean river water given in Viers et al. (2000). Dissolved phosphate is below the detection limit due to the high sorption capacity of the Fe(III),Al-rich ferralsols.

The cation and nutrient potassium (K) ranges from 1.1 mg/l to 26.2 mg/l in urban groundwater with one outlier of 65 mg/l. The rainwater background for K in Yaounde is 0.4 mg/l K ± 0.3 (Kuitcha et al., 2012). The observed groundwater concentrations are a factor of 2–3 higher than those in rural settings in Eurasia and Africa (Banks et al., 2002). Springs have a slightly higher median (7.4 mg/l) compared to dug wells (6.9 mg/l, Table 1 in Appendix A). The spatial distribution of K in the acidic environment with regard to the spatial clusters is identical to the spatial distribution of total inorganic nitrogen (TIN) presented in Fig. 3 below (K in Fig. 10 in Appendix A). K is low in the dug wells of the upstream Ekoudou spatial cluster (close to recharge, fringe of settlement), while just a few metres downslope in the Messa Carrière spatial cluster high concentrations of up to 20 mg/l K are found in the dense, unplanned settlement. An immediate onset of mineralization with beginning of settlement has been documented by Fantong et al. (2013) for the transition from “inselbergs” to their settled slopes. *Maximum* K-concentrations are found considerably downstream in the dense urban settlement of Madagascar. Yet, similar concentrations of K are found around the hydrologically isolated hill of Ngoa Ekèlè with many student dorms and also in the developed Biyem Assi/Obili quarter. It can be assumed evident that K in groundwater is related to the proximity of anthropogenic input, as follows from the high concentration of KCl in human urine (Putnam, 1971).

The spatial distribution of total inorganic nitrogen (TIN) as the analytical sum of nitrogen in nitrate (NO3), ammonium (NH4) and nitrite (NO2) is given in Fig. 3. It is virtually identical to K and particularly evident in the Messa Carrière cluster, close to recharge. Urban and periurban agriculture may be factor in lowland flood zones (Nguegang, 2008) where mineral fertilizer is increasingly being used and likely has a bearing on K and TIN in flood plain groundwater. At the green fringes of the city (Ekoudou), where absolute concentrations in groundwater are still low and acceptable (WHO, 2004), nitrogen input is clearly noticeable.

The relationship of the TIN-compounds nitrate, ammonium, potassium (K) and chloride (Cl) in groundwater (dug well: triangle, red; spring: cross, blue; drilled well: barrel, black) is plotted with a matrix cross plot in Fig. 4, where surface water (lake: cross, green; stream: diamond, cyan) is given for comparison, adding the numerical linear spearman-rank coefficients.

The spearman-rank coefficient for the two dominating nitrogen compounds with chloride is similar and positive (Cl/NO3 = 0.620), but stronger for ammonium (Cl/NH4 = 0.675). The relation between chloride and nitrogen becomes significantly stronger with TIN (Cl/

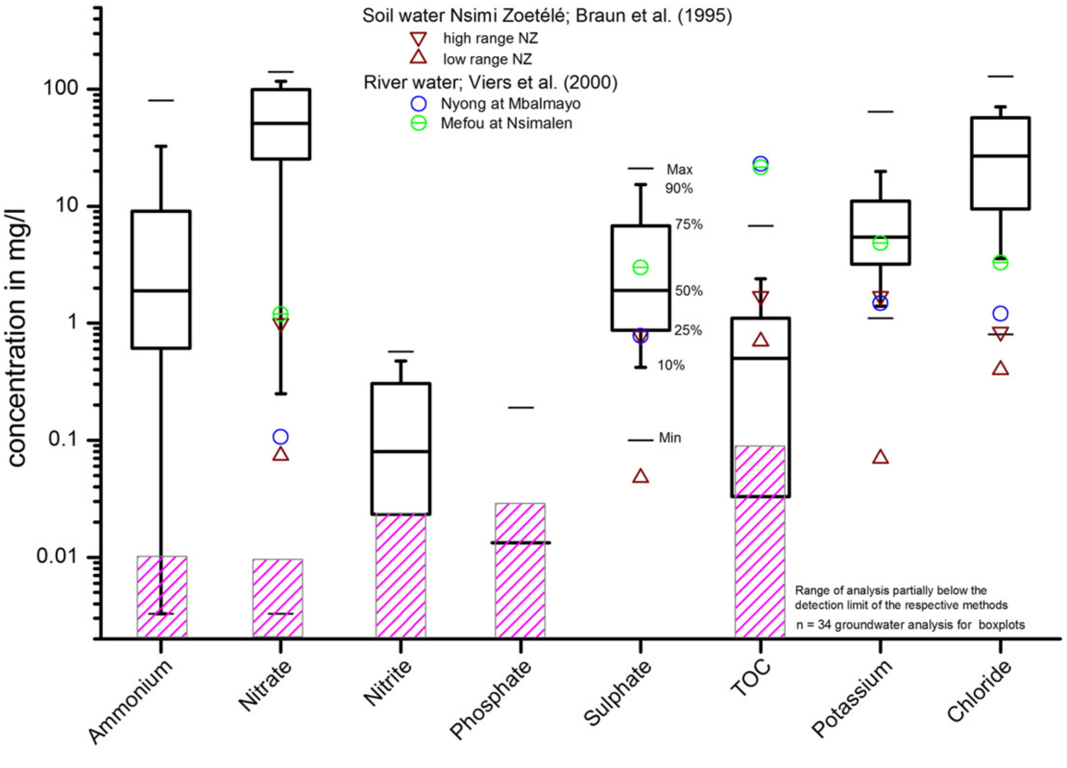

**Fig. 2.** Boxplot of nutrient related parameters in urban groundwater compared to geogenic background concentration from ferralitic soil profiles under forest (Braun et al., 2005) — mean concentrations of two receiving rivers (Viers et al., 2000) given for reference; concentrations in mg/l, upper NZ range from the weathering front (saprolite).

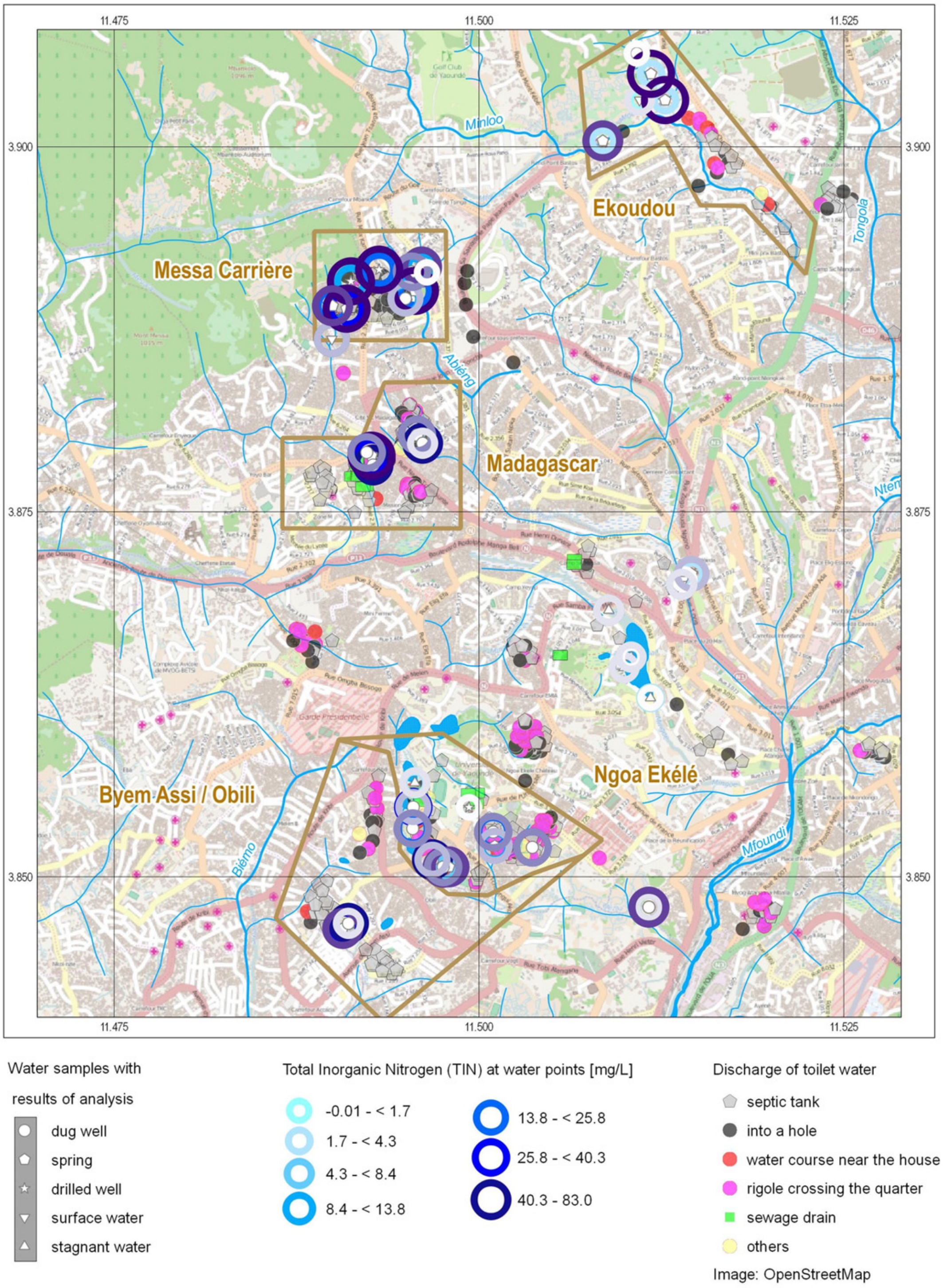

**Fig. 3.** Spatial distribution of total inorganic nitrogen (TIN) in groundwater and surface water in mg/l; Location of sampling sites with the attributed households of the survey in the study area. The five spatial clusters serve to outline different conditions of hydrology and landuse; basemap: OpenStreetMap contributors (2015) licence CC-BY-SA 2.0.

TIN = 0.829). Another nutrient correlation of similar strength is (Cl/K = 0.818). A weak nitrite correlation with TIN or Cl is omitted. Correlations from a molar perspective of the nutrient elements (NPK) may reflect physiological constraints and give additional information (Fig. 11 in Appendix A). Excluding two contaminated wells, the p50 of the Na/Cl ratio is 1.34 (seawater: 0.859), the p50 of TIN/Cl ratio is 1.42 with a considerable range and the p50 for K/Cl ratio is 0.27. The range of the K/Cl ratio is much narrower than the TIN/Cl ratio. This indicates that a lower share of chloride is associated with nitrogen than with the alkaline metals. The alkaline metals have a p50 K/Na ratio of 1/5.

### *3.2. Formation of anthropogenic groundwater types*

The electrical conductivity (EC) of urban groundwater ranges from 33 μS/cm to 1028 μS/cm at the end of the dry season. Analytical TDS ranges from a spring with 27.4 mg/l to a dug well with 1023 mg/l with a p50 of 195 mg/l. A strong linear correlation ($R^2 = 0.96$) exists for EC and TIN as seen in Fig. 5 with the function $\text{TIN} = 0.0714 \times \text{EC} - 2.57$. Dug wells appear to have reduced TIN compared to springs which contain little ammonium. Three groundwater samples were excluded for their known historic or present waste water input

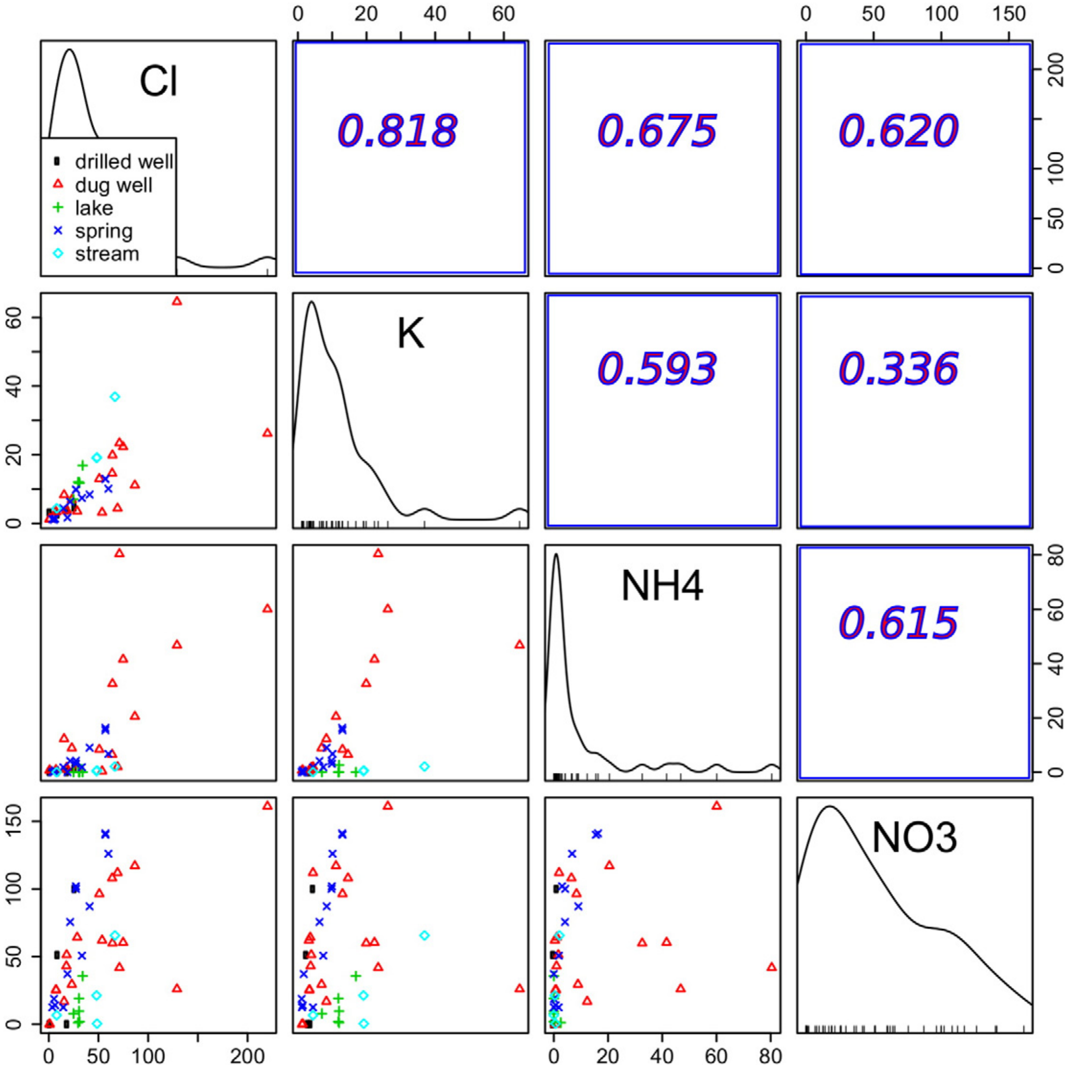

**Fig. 4.** Crossplot of nitrogen-compounds (nitrate, ammonium, chloride and potassium in Yaounde groundwater and surface water; axis values are in mg/l, Pearson rank correlation coefficients given above slant.

and surface water samples are outside of this correlation. By contrast, TDS in rainwater of a forest catchment (IDAF5) is slightly above 1.5 mg/l (Sigha-Nkamdjou et al., 2003). The range of geogenic groundwater for this site (Braun et al., 2005) is given in Fig. 2. Rainwater in the urban Mfoundi watershed (Kuitcha et al., 2012) with an EC of 30.6 µS/cm ± 19.7, 1.3 mg/l Cl ± 0.7 and 0.7 mg/l $NO_3^-$ ± 0.7, has approximately twice the annual, volume weighted mean concentrations as the forested IDAF5 Nsimi Zoetélé site with 0.15 mg/l Cl, 0.43 mg/l $NO_3^-$ and 0.18 mg/l $NH_4^+$ (Galy-Lacaux et al., 2008).

The measured EC in urban groundwater start near to the geogenic background and the mean value for weakly mineralized, tropical urban rainwater (Kuitcha et al., 2012). It ranges up to highly mineralized groundwater — not to be expected in natural environments of the tropical zone because of the strongly positive water balance. For Yaounde TIN-concentration *can be predicted* with the robust (but calibrated) measurement of EC. This linear correlation holds true as long as water points are avoided where direct contamination by point sources can be found and carbonates are absent from the aquifer and the soil zone. On the contrary the concentration of individual nitrogen compounds is largely subject to processes in the aquifer.

However, qualifying a groundwater as "anthropogenic" requires geochemical classification of the water type and cannot be based on high TDS/EC only. The spectre of groundwater types, additionally classified by the percentiles of EC, is found in the piper diagram (Piper, 1944) in Fig. 6 adapted to include nitrate and ammonium. The only Ca–$HCO_3$-type groundwater samples originate from two deep production wells. All other samples direct towards the Na + K + NH4 corner of the cation triangle and the Cl + $NO_3$ corner of the anion triangle. Neither nitrate nor ammonium may be omitted from the hydrochemical classification as main components. Another feature are low sulphate equivalents combined with very low absolute concentrations (Table 1, Appendix A).

While groundwater from the lower fractured aquifer may yield Ca-HCO3 type water of good quality, the much more productive porous ferralsol aquifer generally yields sodium, potassium and nitrate dominated groundwater types with little or no alkalinity (Kuitcha et al., 2013). The general trend of quality development is from rainwater to geogenic groundwater and onward towards anthropogenic Na-K-Mg-Cl-NO3-HCO3-type groundwater due to the massive input of wastewater/urine. The most conspicuous water types — to our knowledge not known in literature for the sub-Saharan region were Na–Ca–$NO_3$*–Cl–$HCO_3$, Na*–Cl–$NO_3$ and an ammonium dominated sample of the type NH4*–Na–$HCO_3$*–Cl.[1]

While anthropogenic influence is easy to identify at high concentrations, the equivalent percentage of nitrate in the sum of anions (Fig. 7) is a much more sensitive measure to detect human impact on

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[1] Where * denotes more than 25% of the anion equivalent.

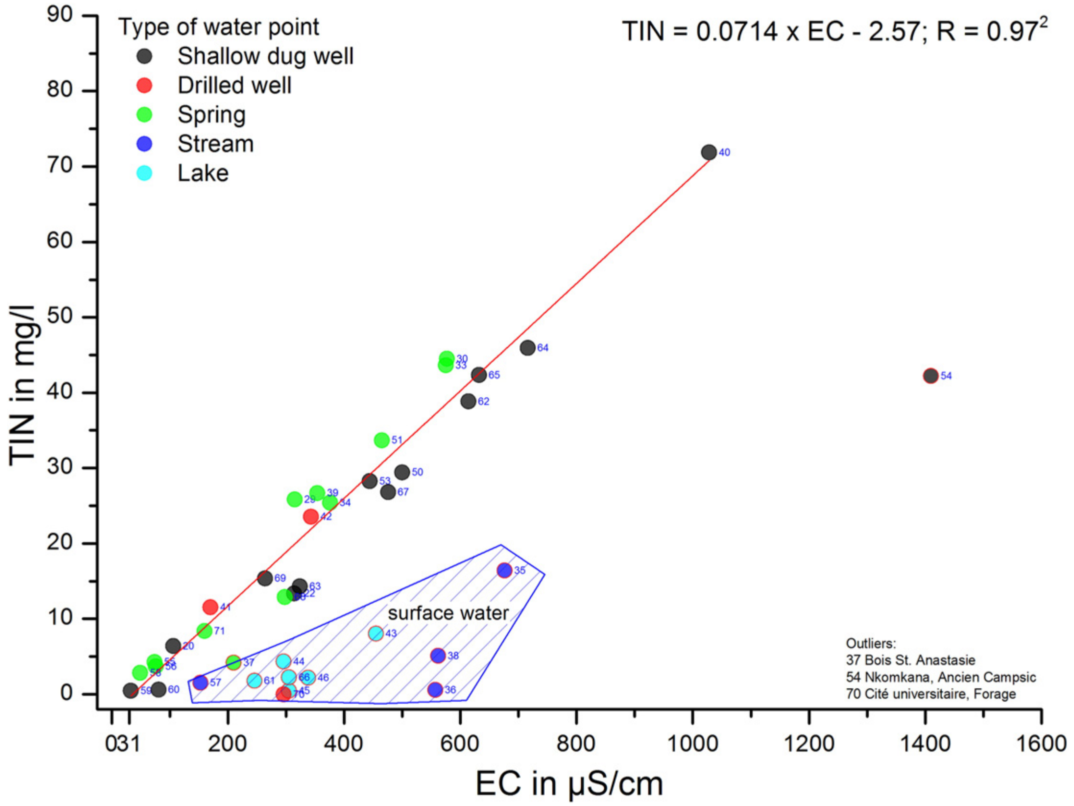

**Fig. 5.** Linear correlation of electrical conductivity (EC) and total inorganic nitrogen (TIN) in groundwater from non-point sources in Yaounde, surface water shown for comparison.

groundwater quality. Fig. 7 shows that the upstream Ekoudou spatial cluster is already strongly influenced by input of nitrate, albeit at low concentrations. The equivalent percentage is at the same level as in the highly contaminated Messa Carrière spatial cluster. Thus, it can be concluded that nitrate input is a general process under urban landuse, regardless of absolute concentrations.

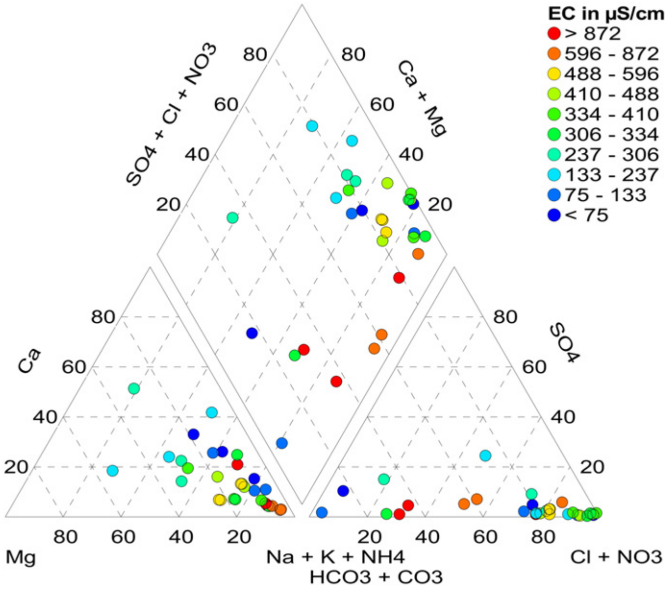

**Fig. 6.** Piper-diagram of 2012 groundwater samples, colour-table depending on percentiles of EC in µS/cm.

### 3.3. Incomplete nitrification in acidic groundwater

Coexistence of ammonium and nitrate in groundwater samples is observed mainly in dug wells. Fig. 8 (top) shows that nitrate frequently accounts for up to 50% (max. 67%) of the anion equivalents in groundwater. The first maximum in Fig. 8 (top) represents 10 surface water samples with lower concentrations than groundwater. Fig. 8 (bottom) indicates that ammonium can also have a considerable share of the cation equivalents in groundwater.

The geochemical environment in Yaounde groundwater is highly oxidizing with a p50 of dissolved oxygen (DO) of 8.1 mg/l (min. DO 3 mg/l). Accordingly, a very low mobility of redox sensitive and dissolved iron (p50 = 0.05 mg/l, 5 outliers) and manganese (p50 = 0.35 mg/l) is observed. The efficiency of nitrification could be affected by environmental factors such as the acidic (<pH 5.5), poorly pH-buffered groundwater (de Boer and Laanbroek, 1989) and the lack of organic nutrients needed by the nitrifying bacteria (see TOC in Table 1, Appendix A). Rao et al. (2015) equally report incomplete nitrification in urban groundwater. Most likely and most conspicuously in the field, the close proximity of innumerous cess pits and the effluent from septic tanks provide a continuous load of ammonium-N along the migration pathways.

### 3.4. Surveying point sources of groundwater contamination

In order to quantify the number of discrete point sources which are prone to contaminate the upper porous aquifer, the groundwater, health and sanitation survey (INS and BGR, 2013) contained a subset of questions aiming at local practises of waste water management in 1134 households.[2] In Yaounde, 1.6% of the households are connected to the central sewer system, while the majority of households use

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[2] The survey showed that up to 24% of the toilet waste water enter the surface drainage network, particularly during rainy season (Fig. 9, left) while the bulk reaches pits and septic tanks.

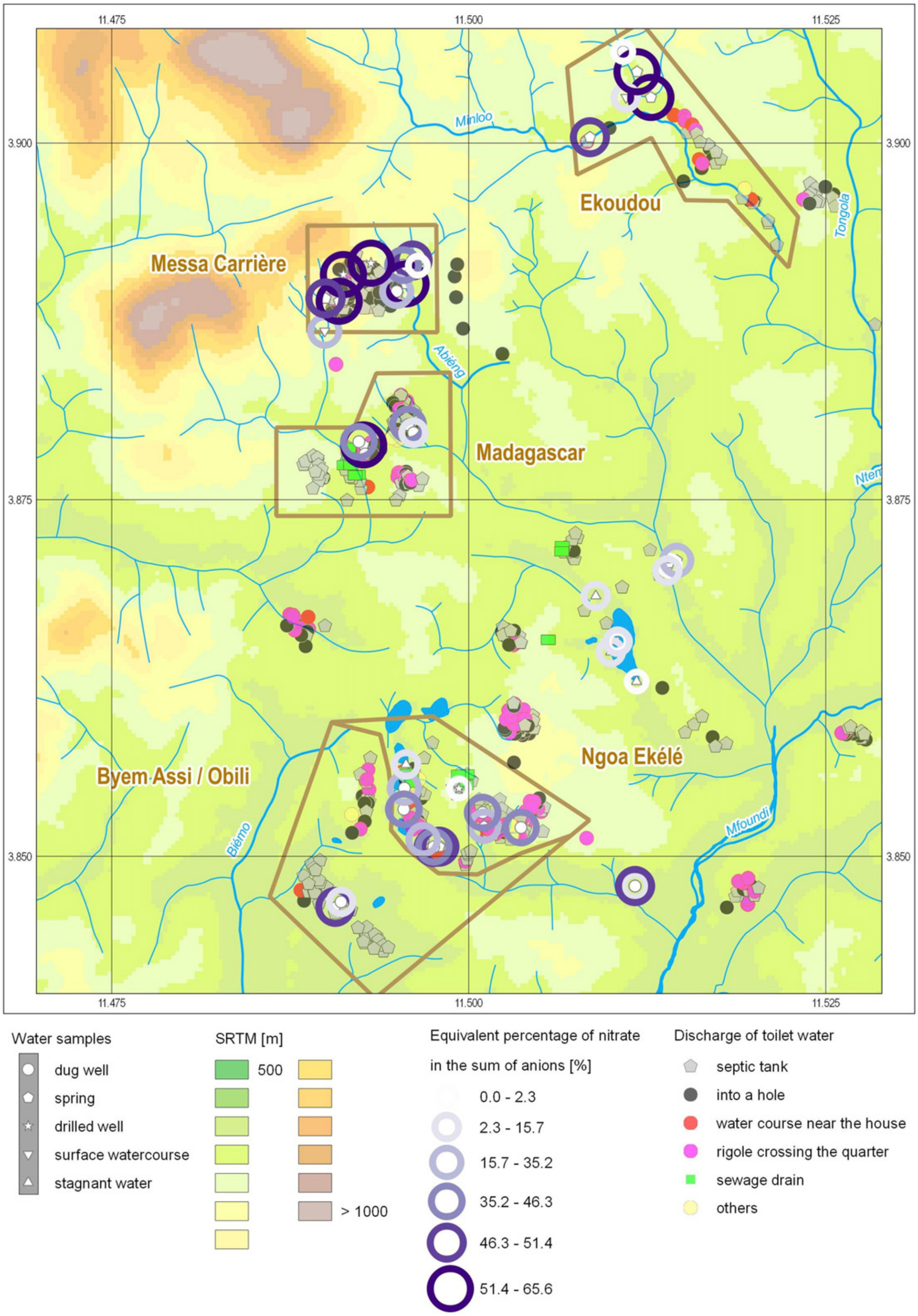

**Fig. 7.** Spatial distribution of the equivalent percentage of nitrate in the sum of anions in groundwater and surface water, SRTM30, Farr et al., 2007.

decentralized sanitation systems (pit or septic tank). The results of question "Common mode of waste water discharge" and question "Common mode of toilet water discharge" are given in Fig. 9 (l, r).

Untreated discharge is 44% (pit latrines) because a septic tank is missing. The frequent use of rigoles (57.7%) may partially contribute to groundwater recharge, yet mainly causes health concerns. It can be concluded that 84% of the toilet water, augmented in volume by 19% of household waste water eventually infiltrates the ferralsol aquifer (INS and BGR, 2013). This anthropogenically enhanced infiltration and eventually recharge will bring with it a proportionate load of inorganic salts (NaCl, KCl) (Putnam, 1971) and nitrogen (TIN) from human excreta.

A relation between households and the number of pit latrines and septic tanks may be estimated by evaluating the question "Do you share your toilet with other housholds?" jointly with question "How many households use the same toilets like you?". 44.3% (n = 504) of the households have a private toilet, while 55.7% (n = 631) of the

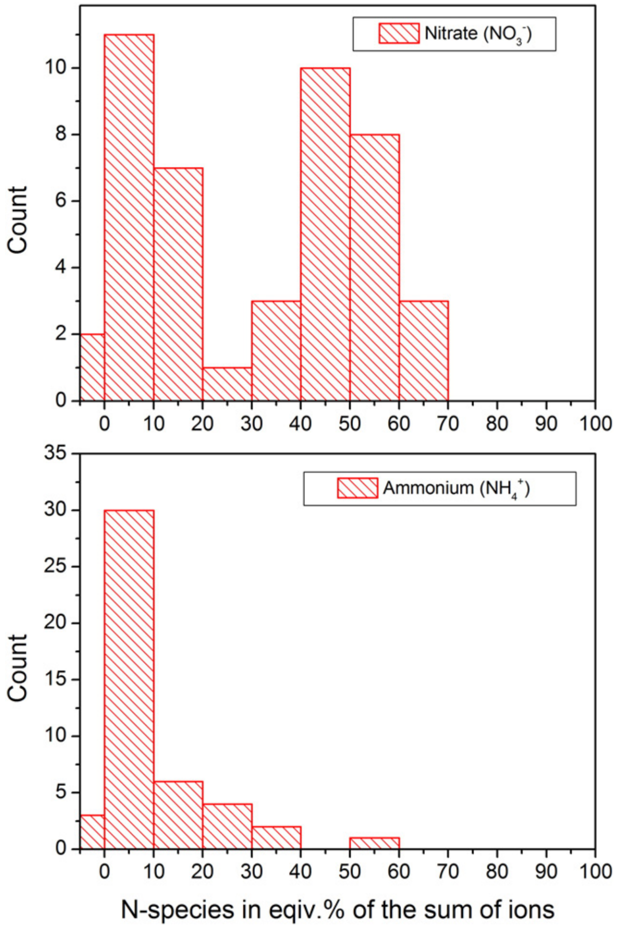

**Fig. 8.** Equivalent proportion of the charge of the nitrate anion (top) and the ammonium cation (bottom) in the charge of anions respective cations in all water samples (n = 49) taken in Yaounde in April 2012.

population use shared toilets (Fig. 9, right). Of those, the modal value for shared toilets appears to be 4 households. Because the class "1 + 7 and more households" is the largest class, a median value of 6 households sharing one toilet can be assumed.

It can thus be concluded that 52% of all households are equipped with a decentralized sanitation type. All these points are potential groundwater contamination sites. The abundance of individual point sources and the hydrodynamic dispersion along the flowpath demands to consider the wastewater input as diffuse, rather than individual plumes (Karamchandani et al., 2002).

### 3.5. Urban turnover of nutrients and their signal in groundwater

Assuming a living population of two million inhabitants (BUCREP, 2010) and taking the human elemental excretion values (urine, faeces) for Uganda (www.ecosanres.org), given in Jönsson and Vinneras (2004) and Richert et al. (2010), the mean yearly excretion of nitrogen (N), phosphorus (P) and potassium (K) by the population would amount to the order of: 4400 t N/a, 600 t P/a (1375 t $P_2O_5$/a) and 2000 t K/a (3636 t $K_2O$/a), respectively. Comparable quantities of nitrate are reported by Houben et al. (2008) for the city of Kabul. Recalculating the annual load into a *hypothetical mean concentration* taking the urban area of 304 $\text{km}^2$ (Fouépé Takounjou et al., 2011), a mean urban infiltration rate of 201 mm/a (Fouépé Takounjou et al., 2011), the mole weight of nitrogen and an unit conversion factor into consideration, would result in a yield of 3.91 $\text{mol/m}^3$ N (mmol/l N), equivalent of 242 mg/l nitrate.

$$4,400\ \text{tons N/a} \times \left(1–0.24^2\right) \times 10^6\ \text{g/tons}/\left(0.201\ \ \text{m/a} \times 304\ 10^6\ \ \text{m}^2\right) \times 14.01\ \text{g/mol} = 3.91\ \ \text{mol/m}^3.$$

A load of 4400 t N/a × 0.76 = 3344 t N/a to the subsurface would hold true if gaseous losses from microbial and physical processes within pit latrines and septic tanks as well as dissimilatory denitrification in the acidic aquifer could be neglected. At present it is not known which N-loss rates might apply for acidic ferralsols both in the unsaturated and the saturated zone under a mean annual temperature of 24 °C (Nyenje et al., 2010). Neglecting all gaseous losses (e.g. Hinkle et al., 2008; Rao et al., 2015) until better knowledge, the predicted level of 242 mg/l nitrate of (area based) mean urban concentration is 4.7 times higher than the observed median of nitrate 51 mg/l in urban groundwater (Table 1, Appendix A), INS and BGR (2013).

The associated estimated load of 2,000 t K/a can be treated identically:

$2000\ \ \text{tons K/a} \times (1-0.24) \times 10^6\ \ \text{g/tons}/(0.201\ \ \text{m/a} \times 304\ 10^6\ \ \text{m}^2) \times 39.09\ \ \text{g/mol} = 0.636\ \ \text{mol/m}^3$.

The *hypothetical mean concentration* of potassium would be 0.636 mmol/l K equivalent to 24.8 mg/l potassium. The observed p50

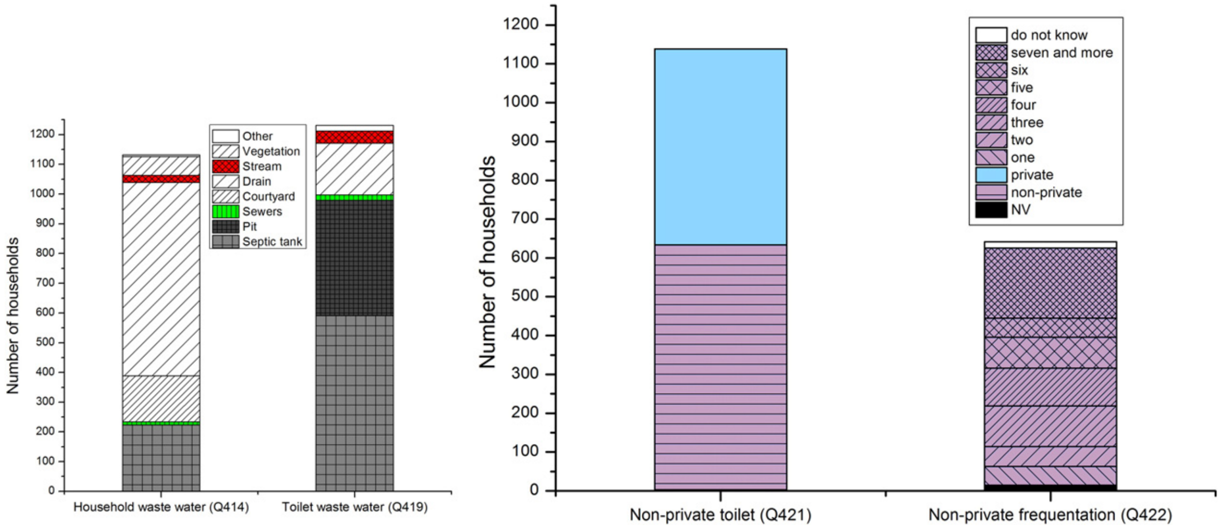

**Fig. 9.** Left: Answers of households on local practises regarding household water discharge and the discharge of black water/faeces, Right: Answers of households on private and shared use of toilets; source: INS and BGR (2013).

in groundwater is 5.5 mg/l, while the p50 of surface water is 12 mg/l. Keeping in mind, that the cation K is expected to leach in the acidic ferralsols for a lack of 3-layer clay minerals (Ngon Ngon et al., 2009) and its positive charge, K can thus be regarded as conservative in comparison to TIN. In this perspective it is extremely surprising that the ratios *hypothetical*:*observed* for N = 242 mg/l: 54 mg/l and for K = 24.8 mg/l: 5.5 mg/l are identical (4.48 = 4.50 to 1) for practical purposes. This result is a strong indication, that dissimilatory denitrification is unimportant or even absent as a process under the oxidizing and acidic, TOC-poor conditions of the ferralsol aquifer. However, for the verification of this hypothesis, N-gaseous emissions and dissolved nitrogen gas concentrations in groundwater would need to be measured and their respective $^{15}$N isotopic signals be determined.

The fate of estimated 600 t P/a is quite different for the geochemical properties of phosphorus favouring sorption and precipitation under the given conditions of the Fe(III),Al-rich aquifer (Ngon Ngon et al., 2009). With just two exceptions, dissolved P is below the detection limit of 30 μg/l (e.g. Table 1) indicating that it is quantitatively sorbed in the urban subsurface.

### 3.6. Loosing nutrients

Larger rivers integrate *soil-landuse-water* interaction for river basins (Caraco and Cole, 1999). Solutes are constantly exported with drainage of the Mefou/Mfoundi river network (Ndam Ngoupayou et al., 2007). Taking the nitrate concentration and discharge given for the Mfoundi River gauge (Nsimalen) in Ndam Ngoupayou et al. (2007), an export of approximately 3,239 t/a nitrate results for a larger fraction of the Yaounde urban area. The equivalent mass of 732 t/a as TN, compares to 22,400 t TN imported in 2012 as mineral fertilizer in all of Cameroon (www.fertilizer.org, IFA, 2015). It illustrates the size and the potential of the urban sanitation problem.

Even though a *large uncertainty* of all parameters (recharge, discharge, population, area) involved in the mass balance estimate has to be taken into account, it can be summarized, that *predicted mean concentrations for infiltration* are still above the observed median groundwater concentration for TIN and nitrate. They are however *within* the observed range of potassium (Table 1, Appendix A).

The remarkable TIN balance gap could only be closed by combined mass balance – hydrological – groundwater modelling approaches, which are outside the scope of this paper. Microbial nitrogen and carbon turnover in pits, septic tanks, the unsaturated zone and the saturated aquifer are currently neglected points, but are assumed to account for only a fraction of this marked difference. Another aspect is the *dynamics of the urban groundwater system* itself. Both the infiltration rate (201 mm/a) as the recharge rate (Fouépé Takounjou et al., 2011) are small in comparison to the volume of groundwater present (approx. 20 000 mm × porosity) in the ferralsol aquifer. An estimate of the mean residence time (recharge rate/volume of groundwater) of water in the urban aquifer system is thus longer than the areal growth rate of the city charted by Tchindjang et al. (2009). Likely, groundwater concentrations have not yet reached *dynamic equilibrium* between input of N,K by loaded recharge and output by exfiltration and surface drainage. This particularly affects cases in newer city quarters. A further deterioration of urban groundwater quality has to be expected.

## 4. Conclusions

It appears that the accurate measurement of electrical conductivity (EC) is a very good predictor for total inorganic nitrogen (TIN) concentration in urban tropical environments where centralized sanitation is rare and the solute contribution from an element depleted, acidic ferralsol aquifer is very low. Decentralized sanitation in pit latrines and septic tanks is effectively controlling groundwater quality formation – to an extent where the geogenic signal is barely detectable. The observed spatial distributions of the nutrient parameters TIN and potassium are almost identical and associated with the density of urban settlement. At the end of formation are anthropogenic groundwater types dominated by nitrate, ammonium and alkaline salts, generated by input of urine and waste water (faeces to a lesser extent), which to the authors knowledge, has not been published so far.

Research needs have been outlined in Nyenje et al. (2010) on nutrient turnover in the tropical, urban environments. Further combined hydrological – mass balance –and groundwater modelling studies could contribute to close the pronounced balance gap for TIN, which was observed in this study.

The poor inorganic groundwater quality found at the end of dry season 2012, highlights the need for urgent measures to a) decrease nitrogen input and b) improve drinking water quality. The inorganic groundwater quality adds to the risks due to microbiological hazards described by various studies (Bemmo et al., 2001; Nguendo Yongsi et al., 2008; Nguendo Yongsi, 2011; Kuitcha et al., 2008; Ateba Bessa et al., 2012) and updated by INS and BGR (2013).

The yearly equivalents of mineral fertilizer contained in toilet waste water and the groundwater quality of Yaounde should be regarded from a nutrient perspective (K,TIN). In a naturally nutrient depleted tropical environment, cities are huge resources of nutrients (Tsegai et al., 2013). Safe (partial) recycling of these nutrients will improve the environmental situation as the way towards efficient centralized or semi centralized sanitation appears unrealistically long. Large, but locally rooted, sanitation schemes, have the potential to a) improve the sanitation challenge and likely to b) improve the groundwater quality situation by reducing the nitrogen load to the urban groundwater by a large factor. Initiatives like EcoSanRes (www.ecosanres.org) provide the scientific knowledge base, integrating aspects of engineering, biology, agriculture as well as important issues of management and public acceptance. Moreover, as an increase in agricultural productivity in production belts around cities will acerbate the concentration of nutrients in groundwater and favour eutrophication of environments downstream.

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## Appendix A

**Table 1**
Distribution (percentiles) of nutrient parameters in urban groundwater of Yaounde compared to geogenic background concentrations from the forested Nsimi Zoetélé site (Braun et al., 2005); concentrations in mg/l, range for cited data.

| Parameter | Group | Min | p10 | p25 | p50[a] | p75 | p90 | Max | n | x | Sd |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ammonium | Dug well | 0.390 | 0.592 | 0.86 | **6.49** | 29.6 | 54.8 | 80.4 | 20 | 17.2 | 23.8 |
| | Spring | 0.003 | 0.003 | 0.51 | **3.05** | 7.3 | 15.7 | 16.3 | 13 | 4.9 | 5.6 |
| Nitrate | Dug well | 0.010 | 6.9 | 25.6 | **51.3** | 88.4 | 115.0 | 161.0 | 20 | 57.9 | 43.4 |
| | Spring | 12.5 | 12.6 | 17.6 | **75.6** | 108.0 | 140.2 | 141.0 | 13 | 70.6 | 49.3 |
| | NZ range | | | **0.074–1.0**[b] | | | | | | | |
| Nitrite | Dug well | <0.07 | 0.023 | 0.075 | **0.30** | 0.36 | 0.55 | 0.57 | 20 | 0.25 | 0.20 |
| | Spring | <0.07 | <0.07 | <0.07 | <**0.07** | <0.07 | <0.07 | 0.41 | 13 | 0.08 | 0.14 |
| $PO4_{sol}$ | Dug well | <0.03 | <0.03 | <0.03 | <**0.03** | <0.03 | <0.03 | 0.03 | 20 | 0.011 | 0.005 |
| | Spring | <0.03 | <0.03 | <0.03 | <**0.03** | <0.03 | 0.33 | 1.6 | 13 | 0.13 | 0.45 |
| Sulphate | Dug well | 0.41 | 0.51 | 0.9 | **1.9** | 5.6 | 16.1 | 18.3 | 20 | 4.9 | 6.1 |
| | Spring | 0.10 | 0.12 | 1.2 | **1.9** | 6.8 | 11.4 | 14.8 | 13 | 3.9 | 4.5 |
| | NZ range | | | **0.048–0.78**[b] | | | | | | | |
| TOC | Dug well | 0.03 | 0.03 | 0.23 | **0.60** | 1.65 | 3.3 | 6.80 | 20 | 1.3 | 1.7 |
| | Spring | 0.03 | 0.03 | 0.03 | **0.20** | 0.80 | 3.6 | 13.20 | 13 | 1.4 | 3.6 |
| | NZ range | | | **0.7–1.7** | | | | | | | |
| K | Dug well | 1.2 | 2.12 | 3.45 | **6.9** | 18.6 | 25.1 | 64.6 | 20 | 12.5 | 14.96 |
| | Spring | 1.1 | 1.18 | 1.63 | **7.4** | 10.0 | 12.9 | 13.0 | 13 | 6.74 | 4.407 |
| | NZ range | | | **0.07–1.7**[b] | | | | | | | |
| Chloride | Dug well | 0.8 | 3.4 | 16.0 | **50.9** | 70.6 | 112.0 | 220.0 | 20 | 52.8 | 53.3 |
| | Spring | 3.6 | 4.9 | 12.5 | **27.3** | 45.1 | 57.6 | 60.0 | 13 | 28.7 | 20.0 |
| | NZ range | | | **0.4–0.84** | | | | | | | |

[a] A range from the Nsimi Zoetélé watershed (landuse forest) is given from Braun et al. (2005).

[b] Maximum concentration from the weathering front in the saprolithe.

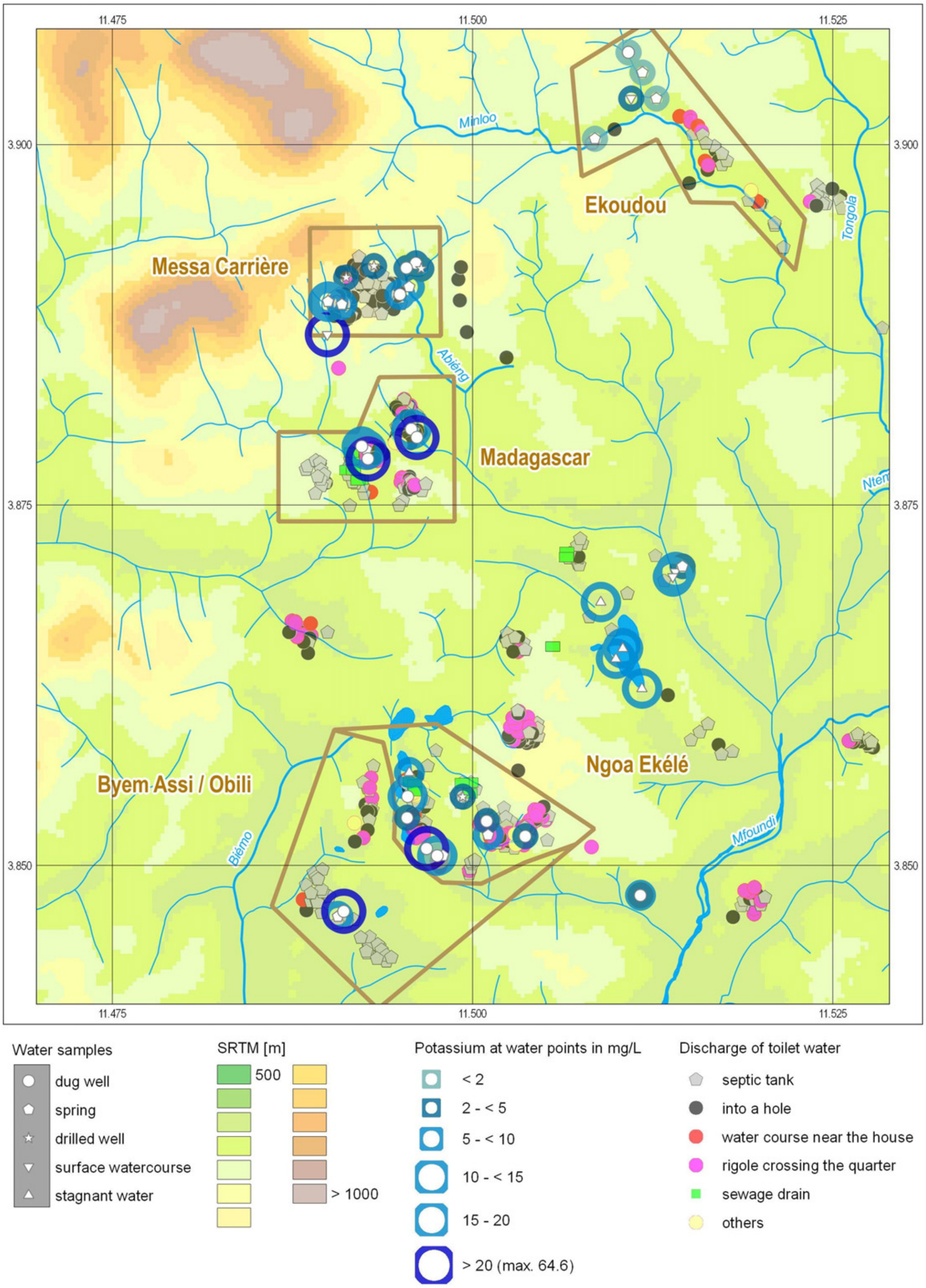

**Fig. 10.** Spatial distribution of potassium in groundwater and surface water; in mg/l, SRTM30, Farr et al., 2007.

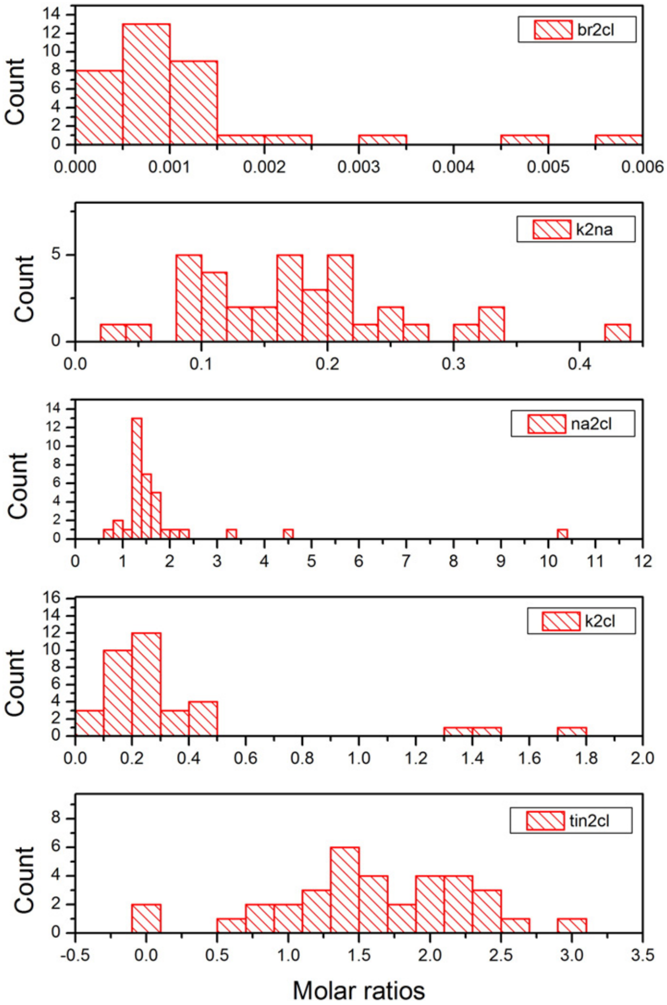

**Fig. 11.** Distribution of the molar ratios of nutrient related parameters in urban groundwater in Yaounde.

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