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

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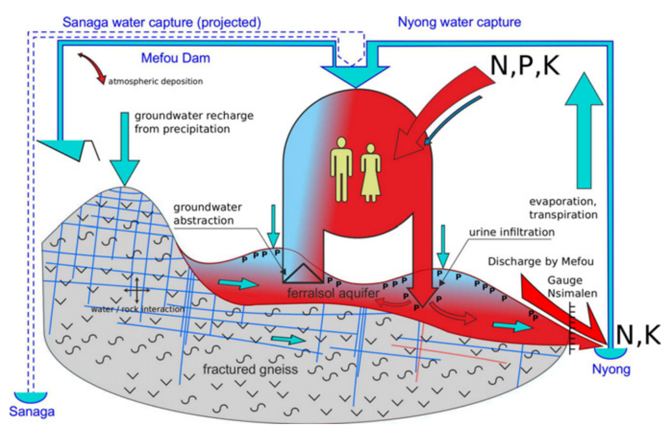
HIGHLIGHTS

- 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.