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1 A review of the socioecological causes and consequences of cyanobacterial  
2 blooms in Lake Victoria

3

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25 **Abstract**

26 Africa is experiencing high annual population growth in its major river basins. This growth  
27 has resulted in significant land use change and pollution pressure on the freshwater  
28 ecosystems. Among them, the Lake Victoria basin, with more than 42 million people, is a  
29 unique and vital resource that provides food and drinking water in East Africa. However,  
30 Lake Victoria (LV) experienced a progressive eutrophication and substantial changes in the  
31 fish community leading to recurrent proliferation of water hyacinth and cyanobacteria. Based  
32 on an extensive literature review, we show that cyanobacterial biomasses and microcystin  
33 concentrations are higher in the bays and gulfs (B&Gs) than in the open lake (OL), with  
34 *Microcystis* and *Dolichospermum* as the dominant genera. These differences between the  
35 B&Gs and the OL are due to differences in their hydrological conditions and in the origins,  
36 type and quantities of nutrients. Using data from the literature, in this paper we describe the  
37 multiple ways in which the human population growth in the LV watershed is connected to the  
38 increasing occurrence of cyanobacterial blooms in the OL and B&Gs. We also described the  
39 already documented consequences of cyanobacterial blooms on food resources and fishing  
40 and on direct water use and water supply of local populations, with their potential  
41 consequences on the human health. Finally, we discuss the actions that have been taken for  
42 the protection of LV. Although many projects have been implemented in the 15 past years in  
43 order to improve the management of waste waters or to reduce deforestation and erosion, the  
44 huge challenge of the reduction of cyanobacterial blooms in LV by the control of  
45 eutrophication seems far from being achieved.

46

47 **Keywords:** Cyanobacteria; Lake Victoria; Eutrophication; East Africa; Potential toxicity;  
48 Socioecological analysis; Consequences of cyanobacterial blooms

49

## 50 **1. Introduction**

51 Numerous studies have been conducted in the past 20 years with the goal of improving our  
52 knowledge of the causes and consequences of cyanobacterial blooms. Taranu et al. (2015)  
53 have shown that the increasing occurrence of cyanobacterial blooms is clearly associated with  
54 the increasing impact of human activities on freshwater ecosystems during the Anthropocene,  
55 and it is well established that the main cause of cyanobacterial blooms is the nutrient  
56 enrichment of phosphorus (P) and nitrogen (N) (O’Neil et al., 2012, Huisman et al., 2018).  
57 Recently, several papers also suggested that climate change might directly or indirectly  
58 promote cyanobacterial blooms (e.g., Moss et al., 2011; Paerl et al., 2016; Ho et al., 2019).  
59 Blooms are also well known to have multiple impacts on the ecological functioning of  
60 freshwater ecosystems (e.g., Paerl et al., 2016; Huisman et al., 2018, Escalas et al., 2019) and  
61 on the goods and services (G&S) they provide (e.g., Dodds et al., 2009). Finally, many papers  
62 deal with the production of harmful toxins by cyanobacteria and the sanitary risks associated  
63 with them (e.g., Briand et al., 2003; Merel et al., 2013; Meriluoto et al., 2017).

64       Among these previous studies, few papers have focused on developing countries, with  
65 the exception of a few countries such as Brazil and China (Merel et al., 2013). In particular,  
66 the issue of cyanobacterial blooms has been poorly investigated on the African continent, as  
67 illustrated recently by Svircev et al. (2019). When looking in this review at the distribution of  
68 cyanotoxins worldwide, it appears that data on cyanotoxins are available only for 14 of the 54  
69 African countries and for 76 ecosystems on the continent. Among these ecosystems, Lake  
70 Victoria (LV) is the most studied, probably because it is the second largest lake in the world  
71 and provides goods and services (G&S) to millions of people (Downing et al., 2014; El-  
72 Noshokaty, 2017). Moreover, LV has experienced rapid water quality degradation that has led  
73 to eutrophication, which is considered a major threat to the ecological function of the lake  
74 (Hecky et al., 1994; Juma et al., 2014) as it results in the recurrent proliferations of aquatic  
75 weeds (e.g., water hyacinth) and cyanobacteria (Lung’ayia et al., 2000; Opande et al., 2004,

76 Juma et al., 2014). The proliferation of water hyacinth has been more or less controlled since  
77 the end of the 1990s with biological, mechanical or physical strategies (Opande et al., 2004;  
78 Wanda et al., 2015), but cyanobacteria blooms persist in LV, particularly in the bays and gulfs  
79 (B&Gs) (Haande et al., 2011; Sitoki et al., 2012; Mbonde et al., 2015).

80 The LV basin has one of the highest population densities in Africa, with several large  
81 cities located along the banks of the large bays and gulfs (B&Gs) (e.g., Kampala in Uganda,  
82 Kisumu in Kenya, and Mwanza in Tanzania) (Figure 1). An understanding of the interplay of  
83 ecological and socioeconomic processes acting directly or indirectly on the lake is of primary  
84 interest. In this context, we address the state of knowledge on (i) the distribution of  
85 cyanobacterial blooms and cyanotoxins in LV; (ii) the social and environmental factors and  
86 processes potentially explaining the occurrence of cyanobacterial blooms, with a particular  
87 emphasis on changes that have occurred in its watershed during the last 50 years; (iii) the  
88 consequences of these blooms on the ecosystem G&S provided by the lake and (iv) the  
89 management practices implemented with the goal of reducing nutrient loads and consequently  
90 the cyanobacterial blooms.

91  
92 **Figure 1.** The Lake Victoria catchment area with major land use occupation. Land use data  
93 obtained from the ESA Climate Change Initiative - Land Cover project 2017, accessed June  
94 2019.

95

## 96 **2. Study site: the Lake Victoria basin**

97 The LV catchment area has a surface area of 184,200 km<sup>2</sup> and is shared between five  
98 countries (Burundi, Kenya, Rwanda, Tanzania and Uganda). As shown in Figure 1, the  
99 catchment is dominated by cropland and grassland, with major build-up areas (for example  
100 Kampala, Kisumu, Musoma and Mwanza) located on the shorelines of the B&Gs. LV is  
101 located 1,100 meters above sea level in East Africa and is the source of the White Nile. The

102 lake is shared between the three countries of Kenya (6%), Tanzania (51%) and Uganda  
103 (43%). LV has a shoreline of 3,500 km with many B&Gs and a 68,000 km<sup>2</sup> surface area,  
104 making it the world's second largest freshwater lake and the largest lake in the intertropical  
105 area (Dobiesz et al., 2010). The maximum depth of the lake is 80 m, the average depth is 40  
106 m, and the residence time of the water is 23 years. As shown by Talling (1966), Lake Victoria  
107 is monomictic, the overturn period occurring between May and August, while early thermal  
108 stratification occurs between September and December and persistent thermal stratification  
109 from January to April (Muggide et al. 2005).

110         Depending on the areas, the general climate of the Lake Victoria basin ranges from a  
111 modified equatorial type characterized by heavy rainfall throughout the year to a semiarid  
112 type characterized by intermittent drought periods. Overall, there are two rainfall periods  
113 (long rains, March-May, and short rains, October-December) with variations ranging from  
114 870 -1,561 mm in Uganda and from 400-2,736 mm in Tanzania. (Kizza et al.,2009). Water  
115 temperature recorded at the surface of the lake range from 23°C to 29°C throughout the year  
116 (Muggide et al., 2005).

117

### 118 **3. Historical and current status of cyanobacteria and cyanotoxins in Lake Victoria**

#### 119 *3.1. Historical and current status of cyanobacterial blooms*

120 **Recent evolution of the LV phytoplankton community.** As shown from paleolimnological  
121 data by Verschuren et al. (2002), the phytoplankton production in LV has increased since the  
122 1930s. Though there is insufficient nutrient data for this time period, it appears that the  
123 phosphorus concentrations increased (from 1.1 to 2.9  $\mu\text{moles L}^{-1}$  between the 1960s and  
124 1990s) and that eutrophication manifested towards the end of the 1980s (Hecky, 1993; Hecky  
125 et al., 2010). The increasing nutrient content led to an increase in the phytoplanktonic  
126 biomasses and shifts in the diatom community, from the dominance of *Aulacoseira* to the

127 dominance of *Nitzschia* (Stager et al., 2009) and in the total phytoplankton community, from  
128 the dominance of green algae (Chlorophyta) and large diatoms (Bacillariophyta) to the  
129 dominance of cyanobacteria (Lehman and Branstrator, 1994; Ochumba and Kibaara, 1989;  
130 Kling et al. 2001; Verschuren et al., 2002; Hecky et al., 2010). This dominance of  
131 cyanobacteria in phytoplankton communities is now frequently found in the three countries  
132 bordering the lake (Kenya, Tanzania and Uganda), particularly in the numerous B&Gs  
133 (Figure 2).

134

135 **Figure 2.** Cyanobacteria blooms in Uganda, Murchison Bay (A); Kenya, Nyanza Gulf (B);  
136 Tanzania, Mwanza Gulf (C) (© Photos: J.F. Humbert, INRAE)

137

138 **Differences in the phytoplankton biomasses and community compositions of the B&Gs**  
139 **and the OL.** As noted by Talling (1987), the physicochemical conditions and microbial  
140 communities of the open lake (OL) are quite different from those of the B&Gs. In the B&Gs,  
141 phytoplankton biomasses are often  $>30 \mu\text{g Chl-a L}^{-1}$ , with cyanobacteria often comprising  
142 more than 60% of the total phytoplanktonic biomass and frequently comprising more than  
143 80% (Table 1). The rest of the phytoplanktonic community is mainly composed of  
144 Chlorophyta, Cryptophyta, Dinophyta and Euglenophyta (e.g., Haande et al., 2011; Sitoki et  
145 al., 2012).

146 In the OL, the phytoplanktonic biomass is generally less than  $20 \mu\text{g Chl-a L}^{-1}$ , and  
147 changes from a dominance of diatoms to a dominance of cyanobacteria are frequently found  
148 (Table 1). The works of Lung'ayia et al. (2000) and Sitoki et al. (2012) in the Nyanza Gulf  
149 and the OL in Kenya suggest that these changes could be partly driven by the alternation of  
150 dry and rainy seasons.

151 Irrespective of the season, cyanobacteria were dominant in the B&Gs, while diatoms

152 were clearly dominant in the OL during the dry season and represented  $\leq 50\%$  of the  
153 phytoplanktonic biomass during the rainy season. In the latter case, cyanobacteria were the  
154 second most dominant group of phytoplankton. Interestingly, Mbonde et al. (2015) have  
155 shown in a comparative study performed in 16 closed and open bays that the degree of  
156 connectivity of these bays to the OL greatly impacts their phytoplankton communities. The  
157 average phytoplankton biovolumes were much higher in the closed bays than in the open  
158 bays, and the same finding was found when considering only the cyanobacterial biovolumes  
159 (Supplemental Fig. 1).

160

161 **Table 1.** Overview of the published phytoplankton biomass (either as biovolume, cells mL<sup>-1</sup>,  
162 or chlorophyll-a estimates), the occurrence and abundance of cyanobacteria, the dominant  
163 species and the cyanotoxin microcystins in Lake Victoria. f.w.: fresh weight. w.w.: wet  
164 weight. MC: microcystins. Nd: not determined. NzG, Nyanza Gulf (Kenya), MB, Murchison  
165 Bay (Uganda); NG, Napoleon Gulf (Uganda); MG, Mwanza Gulf (Tanzania) (see the  
166 Supplemental Fig. 1 for the location of these sites ) \**Dolichospermum* genus name is used  
167 instead of *Anabaena*.

168

169 **Main cyanobacterial genera found in Lake Victoria.** A great diversity of cyanobacterial  
170 taxa, including both nitrogen fixing taxa such as *Dolichospermum*,  
171 *Cylindrospermopsis/Raphidiopsis* or *Anabaenopsis* and nonnitrogen fixing taxa such as  
172 *Microcystis*, *Planktolyngbya*, *Merismopedia*, *Cyanodictyon* or *Aphanocapsa*, is often found in  
173 B&Gs and the OL (Table 1). An underlying dominance of *Dolichospermum* spp. or  
174 *Microcystis* spp. cyanobacteria has been observed in the literature depending on the location,  
175 year and month of sampling considered. For example, Gikuma-Njuru et al. (2013a) observed  
176 a dominance of *Dolichospermum* and small cyanobacteria such as *Cyanodictyon* and  
177 *Aphanocapsa* between March 2005 and March 2006 in the Nyanza Gulf (Kenya), while Sitoki  
178 et al. (2012) found that *Microcystis* was clearly the most dominant cyanobacteria in the same



179 area from July 2008 to September 2009. In Murchison Bay (Uganda), *Microcystis* dominance  
180 was noted by Poste et al. (2013), whereas the dominance of *Dolichospermum* was found in  
181 Murchison Bay and the Napoleon Gulf by Okello and Kurmayer (2011) and Okello et al.  
182 (2010a). Similar observations and alternations between a dominance of *Dolichospermum* and  
183 a very diversified cyanobacterial community were also observed by Haande et al. (2011),  
184 depending on the date and the sampling station within Murchison Bay. In Tanzania,  
185 Sekadende et al. (2005) found a dominance of diatoms and cyanobacteria belonging to the  
186 *Planktolyngbya* genus in the Mwanza Gulf between May and August 2002. Several years  
187 later, Mbonde et al. (2015) observed a dominance of *Dolichospermum* and *Microcystis* in the  
188 different B&Gs of Tanzania, including the Mwanza Gulf, between November and December  
189 2009.

190         There is no clear explanation for these spatial and temporal variations in the dominant  
191 cyanobacterial genera, but it is known that variations in nutrient concentrations can influence  
192 the composition of cyanobacterial communities. For example, it has been proposed that high  
193 proportions of N-fixing cyanobacteria such as *Dolichospermum* sp. could be linked to a  
194 nitrogen limitation in the lake (Mugidde et al., 2003; Gikuma-Njuru and Hecky, 2005). In the  
195 same way, many studies have shown that *Microcystis* sp. is the most common bloom-forming  
196 species in freshwater ecosystems with high phosphorus concentrations (e.g., Poste et al.,  
197 2013).

198

### 199 3.2. Cyanotoxin production

200 *Microcystis* and *Dolichospermum* genera are well known as the main potential producers of  
201 cyanotoxins of the microcystins (MC) family, but *Dolichospermum* is also known to produce  
202 several families of cyanotoxins including anatoxin-a (ATX) (Bernard et al., 2017). To our  
203 knowledge, all studies in LV have focused on MC, and only one study performed in the

204 Nyanza Gulf (Kenya) focused on ATX (Kotut et al., 2006). Although *Dolichospermum* was  
205 dominant and *Microcystis* was marginal, ATX was undetectable in both environmental  
206 samples and in the isolated strains. During the same study period, the estimated MC  
207 concentration was approximately  $1 \mu\text{g eqMC-LR.L}^{-1}$  (Krienitz et al., 2002; Kotut et al., 2006).  
208 Some of these cyanobacteria are also known to potentially produce other cyanotoxins such as  
209 the amino acid variant  $\beta$ -methyl-amino-L-alanine (BMAA) and saxitoxins, but these  
210 cyanotoxins have not been investigated in LV.

211 Numerous studies have dealt with the detection of MC in LV (Table 1). The first study  
212 reporting the presence of MC was that of Krienitz et al. (2002) and was performed in the  
213 Nyanza Gulf (Table 1). After this first study, MC occurrence was recorded in different parts  
214 of the lake, mainly in the B&Gs but also in the OL in some cases (Sekadende et al., 2005;  
215 Sitoki et al., 2012) (Table 1). Highly variable concentrations of MC were found in LV, from  
216 less than  $1 \mu\text{g.L}^{-1}$  in Murchison Bay (Uganda) (Semyalo et al., 2010) up to  $81 \mu\text{g.L}^{-1}$  and  $>2$   
217  $\text{mg.L}^{-1}$  in Nyanza Gulf (Kenya) (Sitoki et al., 2012; Simiyu et al. 2018, respectively), the  
218 highest concentrations being found in scums or at the surface of the lake (Table 1). A positive  
219 correlation between the MC concentrations and *Microcystis* abundance was found by Okello  
220 et al. (2010a, b), Sitoki et al. (2012) and Mbonde et al. (2015). Finally, Okello et al. (2010b)  
221 observed during a one-year monitoring study (May 2007-April 2008) that the proportions of  
222 the *mcyB*<sup>+</sup> genotypes (potentially producing MC) in *Microcystis* populations varied from  
223 3.3% to 39.2% in Murchison Bay and from 12.9% to 59.3% in the Napoleon Gulf.

224 So far, 240 MC variants have been described in the world (Spoof and Catherine,  
225 2017), but only a few studies have investigated the MC variant composition in the  
226 cyanobacterial blooms from LV (Table 1). Nevertheless, up to seven different variants have  
227 been identified by Okello and Kurmayer (2011) and up to 31 variants have been identified by  
228 Miles et al. (2013). However, the most common variants detected in the lake are MC-LR,

229 MC-RR and MC-YR (e.g., Okello and Kurmayer, 2011, in Murchison Bay and the Napoleon  
230 Gulf; Sitoki et al., 2012, in the Nyanza Gulf; Mbonde et al., 2015, in the Mwanza Gulf). The  
231 proportions of all these MC variants were highly variable depending on the sampled area. For  
232 example, the average estimated proportions of the MC-LR variant in the Murchison Bay and  
233 the Napoleon Gulf (May 2007 - April 2008) were  $12.4\pm 2\%$  and  $0.5\pm 0.3\%$ , respectively,  
234 according to Okello and Kurmayer (2011) but reached  $50\pm 6\%$  in the Nyanza Gulf (July 2008  
235 - Sept 2009) (Sitoki et al., 2012). The small standard deviations associated with these  
236 proportions seem to express low temporal variations for a given area in LV. However, higher  
237 variations are sometimes reported in the literature, as shown for example by the large standard  
238 deviation found in the mean proportion ( $31\pm 52\%$ ) of the MC-YR in the Nyanza Gulf (Sitoki  
239 et al. 2012).

240

241

#### 242 **4. Linking demographic changes with the increasing occurrence of cyanobacterial** 243 **blooms**

244 From the analysis of the data available in the literature on the causes of cyanobacterial blooms  
245 in LV, we built a flow diagram (Figure 3) describing the multiple ways in which the human  
246 population growth in the LV watershed is connected to the increasing occurrence of  
247 cyanobacterial blooms in the OL and B&Gs.

248

249 **Figure 3.** Links between the increase in the human population density around Lake Victoria  
250 and the occurrence of cyanobacteria blooms in the open lake and in the bays and gulfs.

251 OM: Organic matter; P: Phosphorus; N: Nitrogen

252

253 As summarized in Figure 3, the increase in the populations density in the LV basin,  
254 such as everywhere in the world, has resulted in increasing food, housing and product  
255 demands (FAO, 2016). All these demands have many consequences on land use in the  
256 watershed, including farming and fishing activities, as well as formal and informal  
257 urbanization and industrial and commercial activities. All these processes are described in  
258 section 4.1. Then, as developed in section 4.2, the changes occurring in anthropogenic  
259 activities and land use have led to increasing nutrient pollution in the OL and B&Gs through  
260 three main processes: the aerial deposition of phosphorus and nitrogen, the discharge of  
261 mineral and organic nutrients by rivers and a decrease in natural purification due to wetland  
262 degradation. Finally, section 4.3 shows why the B&Gs are more polluted than the OL and the  
263 processes leading to the decrease in water quality.

264

#### 265 *4.1. Determinism and consequences of human population growth in the LV watershed*

266 **Demographic data on the LV watershed.** The African continent continues to experience a  
267 high annual population growth estimated at 2.6% per year in its major river basins (World  
268 Population Prospects, 2017). The population density in the LV basin almost doubled over the  
269 past 20 years from 27.2 million to ca. 42 million inhabitants (Bremer et al., 2013), which is  
270 considered the largest human population in the watersheds of the great lakes of the world  
271 (Dobiesz et al., 2010). This population increased by 2.4 – 3.2% annually (> 6% in some urban  
272 areas such as Kampala, Uganda; McDonald et al., 2014), a growth rate that is higher than that  
273 observed in the rest of the African continent (UNEP, 2006). The data from the Center for  
274 International Earth Science Information Network - CIESIN - Columbia University (2018)  
275 indicates that the population density in major cities has increased from a max of 100 persons  
276 per km<sup>2</sup> to over 23,000 persons per km<sup>2</sup> in the last two decades. A strong and similar  
277 exponential population increase has been observed since the 1960s in Kenya, Tanzania and

278 Uganda (Supplemental Figure 2). On the other hand, Burundi and Rwanda, which  
279 experienced civil war in the 1990s and do not have direct access to the lake, have seen much  
280 lower population growth.

281  
282 **Causes of this population growth in the LV watershed.** A recent report of the International  
283 Institute for Sustainable Development (Dazé and Crawford, 2016) pointed out that migration  
284 in the Great Lakes Region in East Africa is due partly to both voluntary decisions to migrate  
285 and forced migration.

286       Concerning the voluntary migration, many people have migrated towards the lake  
287 basin to take advantage of the economic benefits linked to the fisheries in the basin (Awange  
288 and Obiero, 2006; Odada et al., 2009). As reported in Mkumbo & Marshall (2015), more than  
289 1,200,000 people are directly or indirectly employed in fisheries, and income from fisheries  
290 supports approximately 4 million people. This makes LV the world's largest host for inland  
291 freshwater fisheries (Simonit and Perrings, 2011).

292       On the other hand, forced migrations have resulted from armed conflicts and violence  
293 in Rwanda and Burundi (from 1993 to 2005) and in the Democratic Republic of Congo (from  
294 1996 to 2002). Many of these migrants are located in rural areas (Dazé and Crawford, 2016).

295  
296 **Consequences of population growth on land use, urbanization and anthropogenic**  
297 **activities.** As established in the diagnostic analysis performed by the Lake Victoria  
298 Environmental Management Project (LVEMP), more than 87% of the inhabitants living in the  
299 LV basin are from the rural populations in Burundi, Kenya, Rwanda and Tanzania (see also  
300 Figure 1), while in Uganda, 94% of the inhabitants living in the LV basin are urban (LVEMP,  
301 2007). Meanwhile, as already observed in the developing world (Montgomery, 2008), the  
302 three countries with direct access to the lake and with livelihoods that rely on the lake have

303 also experienced rapid urbanization that has led to the development of large cities located on  
304 the B&Gs, such as Kampala (>2 million inhabitants) on Murchison Bay (Uganda), Kisumu  
305 (approximately 1 million inhabitants) on the Nyanza Gulf (Kenya) and Mwanza (>400,000  
306 inhabitants) on the Mwanza Gulf (Tanzania) (Supplemental Fig 3).

307         The main consequence of increasing population densities in rural areas is a change in  
308 land use, particularly to cropland (see Figure 1). The agricultural development involves ca. >  
309 80% inhabitants' that depend on small-scale mixed farming operations, thus, influencing the  
310 land use. As highlighted in the LVEMP report (LVEMP, 2007), agricultural development  
311 includes wetland destruction and/or degradation, livestock overgrazing, bush burning, land  
312 fragmentation, and deforestation. Deforestation (for settlement and agriculture development)  
313 is spreading at an alarming rate, e.g., in Uganda between 2000 and 2015, the deforestation  
314 rate was 3.3% annually, which is higher than that in other countries of the watershed (0.2%  
315 for Burundi, 0.3% for Kenya, 1.7% for Rwanda and 0.8% for Tanzania) (FAO, 2015). This  
316 deforestation rate has increased from 1990-2015 in Uganda (from 2.0% in 1990-2000 to 3.3%  
317 in 2000-2010, reaching 5.5% in 2010-2015). In typical developing countries, both rural and  
318 urban populations depend heavily on the forest environment and products, such as building  
319 materials, crafts, firewood, charcoal, food, flavoring, and traditional medicine, for their  
320 livelihood (UNEP, 2008; Mwavu & Witkowski, 2008).

321         The drivers of deforestation identified in the LV watershed can be classified into two  
322 broad categories (Waiswa et al., 2015). The direct human uses of forest resources (Geist &  
323 Lambin, 2002; Mwavu & Witkowski, 2008) include the unplanned spread of agricultural  
324 areas over forest areas, firewood and timber harvesting, clearing forestland for human  
325 settlement, sand mining and brickmaking. The indirect drivers concern the underlying  
326 sociopolitical factors impacting human practices, such as unclear land tenure and/or property  
327 rights, lack of forest monitoring and the noninvolvement of users in forest maintenance,

328 conflicts of interest, political interference, and negative perceptions about planning policies  
329 (Place & Otsuka, 2000; Mwavu & Witkowski, 2008).

330

#### 331 *4.2. Relationships between land use changes and the eutrophication of LV*

332 As shown in Figure 3, various processes associated with land occupation changes and  
333 activities have led to the eutrophication of the OL and B&Gs. Numerous studies have focused  
334 on identifying the different processes that lead to nitrogen and phosphorus pollution in LV,  
335 and four main processes have been identified. These processes include (i) the discharge of  
336 rivers from heavily polluted catchments (Verschuren et al., 2002; Musungu et al., 2014;  
337 Fuhrimann et al., 2015; Jovanelly et al., 2015); (ii) atmospheric deposition, in particular of  
338 phosphorus (P) (accounting for 55% of the total phosphorus input in LV) (Tamatamah et al.,  
339 2005); (iii) the biological fixation of atmospheric dinitrogen (N<sub>2</sub>), which seems to greatly  
340 exceed the contributions of atmospheric N deposition and river N inputs (Mugidde et al.,  
341 2003); and to a lesser extent, (iv) nutrient recycling and release from the sediments (Gikuma-  
342 Njuru et al., 2010).

343 The two first nutrient pollution pathways for LV water are directly linked to human  
344 population growth and activities. First, changes in land use patterns have contributed to  
345 enhanced erosion. In Uganda and Tanzania, the presence of settlements on the LV shoreline  
346 zone were associated with high soil erosion estimates of between 17 and 87 ton. ha<sup>-1</sup>.yr<sup>-1</sup>  
347 (Isabirye et al., 2010). The rate of soil loss in the LV basin also appears to depend on the land  
348 use system (tree plantation versus grassland) (Bamutaze et al., 2017). Other human-induced  
349 disturbances, such timber harvesting and soil compaction by cattle, also increase the risk of  
350 soil erosion (Karamage et al., 2017). Similarly, TP and TN atmospheric deposition mainly  
351 seem to result from burnt biomass, windblown dust and industrial and domestic activities (see  
352 the review of Cheruiyot and Muhandiki, 2014).

353           Second, due to the urban human population growth, increasing quantities of solid and  
354 liquid waste originate from (i) the human populations living in the large cities located near the  
355 B&Gs and (ii) industrial activities such as the activities of large manufacturers of steel  
356 construction materials, factories that produce batteries, soap, paint, metal, plastics, corrugated  
357 iron sheets, or pharmaceuticals, and breweries, tanneries, former copper smelters and abattoirs  
358 (Muwanga and Barifaijo, 2006). Moreover, as shown by Cockx et al. (2019) in Tanzania, the  
359 urbanization of the rural population results in changing food demands, which include  
360 increasing consumption of high-sugar foods and drinks. These changes in the demand for  
361 food have led for example to the installation of bottling factories in the three main cities  
362 located around the lake (Kampala, Mwanza and Kisumu). For Kampala (Uganda), only ca.  
363 8% of all wastes (domestic and industrial) are collected and treated (Matagi, 2002), and the  
364 efficiency of the sewage treatment plants is poor, with up to ca. 89% frequency of  
365 noncompliance with the national standard for BOD<sub>5</sub> (LVEMP, 2005). In the same way,  
366 Oguttu et al. (2008) have shown that point source effluents due to increasing industrial  
367 activities in the Jinja area have contributed to the increasing nutrient loads in the Napoleon  
368 Gulf.

369           Finally, the progressive reduction and degradation of wetlands has played a major role  
370 in the degradation of water quality. This degradation is due to housing, industrialization,  
371 infrastructure development and agriculture (Kansiime & Nalubega, 1999; Fuhrmann et al.,  
372 2015). In the Kampala Metropolitan Area (Uganda), the proportion of severely degraded  
373 wetlands increased from 13% in 1993 to 46% by 1999 (Nyakaana et al., 2007). In particular,  
374 Nakivubo wetlands experienced a 62% loss in wetland vegetation between 2002 and 2014,  
375 mainly due to crop cultivation (Isunju, 2016), despite their high estimated economic value of  
376 between US\$ 760,000-1,300,000 (Schuijt, 2002). Similar observations have been made for the  
377 Nyanza Gulf in Kenya by Juma et al. (2014). In Tanzania, Musamba et al. (2011), showed



378 that an increase in the anthropogenic activities in the Musoma urban area was associated with  
379 the degradation of wetland coverage at the average rate of 6.5 ha yr<sup>-1</sup> between 2001 and 2008.  
380 Knowing that wetlands are located at the mouths of the major rivers and in the inshore areas  
381 of the lake (Okeyo-Owuor et al., 2012) and that they play a major role in waste removal and  
382 water purification (Raburu et al., 2012), their degradation contributes to the decrease in water  
383 quality in the B&Gs.

384 The consequences of all these processes acting on the nutrient load in Lake Victoria is  
385 that high concentrations in soluble elements (SRP, NO<sub>3</sub> and NH<sub>4</sub>) have been recorded in the  
386 twenty past years in the Lake Victoria (Supplemental Table 1). The average TN:TP ratios are  
387 almost double in B&Gs (14.5) than in OL (8.1) (Muggide et al., 2005). This suggests that there is  
388 a global N limitation in Lake Victoria, which is more pronounced in offshore area.

389

#### 390 *4.3. Why do the bays and gulfs of LV have more cyanobacteria blooms than the open lake?*

391 Two main kinds of processes seem to be involved in the greater amount of eutrophication  
392 observed in the B&Gs compared to the OL.

393 First, several big towns are located on the banks of the B&Gs, such as Kampala on the  
394 Murchison Bay, Kisumu on the Nyanza Gulf and Mwanza on the Mwanza Gulf. As shown by  
395 Akurut et al. (2017) for the Murchison Bay (Uganda), the exponential deterioration of the  
396 water quality between 2001 and 2014 was largely due to increasing quantities of waste  
397 generated in Kampala City and discharged in the bay. Similar observations were made by  
398 Cornelissen et al. (2014) for the Mwanza Gulf (Tanzania). Several B&Gs also receive water  
399 from rivers carrying high nutrient loads resulting from agricultural farmland in the catchment.  
400 This contribution has been shown for example for the Nyanza Gulf (Kenya) by Gikuma-Njuru  
401 et al. (2013b). As already described in paragraph 3.2, the decrease in the natural depuration in  
402 the wetlands located in the B&Gs contributes to their hyper eutrophication.

403           Second, the hydrodynamic conditions experienced by the B&Gs favors cyanobacteria  
404 blooms. In the closed B&Gs (e.g., Murchison Bay, the Nyanza and Mwanza Gulfs)  
405 experiencing limited exchange with the OL, the water residence time is long, and the high  
406 nutrient load from their watersheds promote and sustain the development of cyanobacterial  
407 blooms. Moreover, the majority of the B&Gs are very shallow, as illustrated by the Nyanza  
408 Gulf, which has a mean depth of <10 m (<5 m in the eastern part of the gulf). Typically, at  
409 shallow depths, all water is mixed daily and there is thermal stratification during high  
410 insolation periods (Gikuma-Njuru, 2008). Consequently, the alternation of mixing and  
411 stratified periods can potentially promote the release of nutrients from the sediments, which  
412 can then sustain cyanobacteria growth (see for ex. Cao et al., 2016). In addition to the mixing  
413 and stratification that occurs at shallow water depths, the high turbidity occurring in these  
414 shallow and mixed B&Gs (Silsbe et al., 2006; Loiselle et al., 2008 & 2010) could promote the  
415 development of bloom-forming cyanobacteria such as *Microcystis* spp. or *Dolichospermum*  
416 spp., which are able to occupy the top of the water column where light is available for their  
417 growth, due to their gas vesicles (Gikuma-Njuru, 2008; Ssebiyonga et al., 2013).

418

#### 419 *4.4. Other processes involved in the increasing occurrence of cyanobacterial blooms in LV*

420 **Role of changes in the fish community.** Nile perch and several tilapiine species (Nile tilapia:  
421 *Oreochromis niloticus* L.; *O. leucostictus*; *Tilapia zillii*) were introduced into the lake in the  
422 1950s and became dominant (Ogotu-Ohwayo, 2004; Awange and Obiero, 2006).  
423 Consequently, Marshall (2018) discussed the possibility that the changes in the fish  
424 community composition during the 1960s could have aggravated the symptoms of  
425 eutrophication and the proliferations of cyanobacteria in the lake. Although Goldschmidt et al.  
426 (1993) emphasized the importance of endemic phytoplanktivorous and detritivorous  
427 haplochromine species in the littoral and sublittoral areas of LV before the 1980s, these

428 species were victims of Nile perch predation, that led to a dramatic decrease in their  
429 biomasses (Marshall, 2018). Thus, in the context of eutrophication, Batjakas et al. (1997)  
430 suggested that the replacement of endemic phytoplanktivorous species by predatory Nile  
431 perch could have facilitated the proliferation of cyanobacterial blooms. Moreover, as  
432 suggested by Marshall (2018), cyanobacteria could have been favored by the decrease in the  
433 population of large phytoplankton grazers from the zooplanktonic community due to their  
434 consumption by juvenile Nile perch. **The other main introduced fish species (Nile tilapia,**  
435 ***Oreochromis niloticus*) is well-known to ingest a diversity of prey items including**  
436 **phytoplankton (e.g. Bwanika et al. 2006). In LV, many authors have reported that the diet of**  
437 ***O. niloticus* often have large proportion of phytoplankton dominated by cyanobacterial**  
438 **species (Semyalo et al, 2011, Rumisha & Nehemia, 2013, Jihulya, 2014). Cyanobacteria has**  
439 **also been shown to contribute to the bulk of the diet of *O. niloticus* in other tropical aquatic**  
440 **ecosystems (Teferi et al. 2000, Turker et al. 2003, Lu et al. 2006, Torres et al. 2016, Zakaria et**  
441 **al. 2019). However, new data on the quantitative predation of cyanobacteria by *O. niloticus***  
442 **are needed before concluding that this species may play a significant top-down role on the**  
443 **dynamics of cyanobacteria.**

444         Since 2005, the stock of Nile perch in LV has rapidly decreased by approximately  
445 50%, mainly due to overfishing (Matsuishi et al. 2006, Mkumbo et al. 2007; Mkumbo and  
446 Marshall, 2015) but also because of the degradation of the water quality (e.g. anoxia). During  
447 the same period, the biomasses of other species such as Nile tilapia, catfishes or *Protopterus*  
448 biomasses have increased because they are less susceptible to degraded water quality  
449 (Kolding et al., 2008). The recent decrease in Nile perch stocks also favored an increase in  
450 haplochromine prey species, although their biomass and diversity remains low compared to  
451 the pre Nile perch era (Marshall, 2018). It is difficult to predict the consequences for  
452 cyanobacterial blooms to all these changes occurring in fish communities of LV knowing that

453 the grazing rates of both fish and zooplankton always have always been low in Lake Victoria,  
454 particularly since the 1980's (Witte et al., 2012).

455 In addition to the changes occurring in capture fisheries, the recent increases in cage  
456 culture farms in the B&Gs (Aura et al., 2018; Opiyo et al., 2018; Musinguzi et al., 2019)  
457 constitutes an additional threat for the lake. It is well known that aquaculture can contribute  
458 significantly to the nutrient enrichment of freshwater ecosystems (Zhang et al., 2006). In  
459 Napoleon Gulf (Uganda), Egessa et al. (2018) observed organic matter and nutrient  
460 enrichment in the sediment due to cage fish farming. In Shirati Bay (Tanzania), an increase in  
461 nutrient concentrations was observed after cage farming establishment (Kashindye et al.  
462 2015), while in Kenya, Njiru et al, (2018) reported increasing eutrophication in shallow areas  
463 due to aquaculture waste feeds. These areas are only small portions of LV where caged fish  
464 farming has occurred, but farming has begun to spread among the various B&Gs of the lake.  
465 Thus, additional data are needed to study this issue and its related consequences on water  
466 quality.

467

468 **Potential impact of climate change.** The potential impact of climate change on  
469 eutrophication in LV and consequently on cyanobacterial blooms has been poorly  
470 investigated. Lehman et al. (1998) suggested that the eutrophication of LV may have been  
471 accelerated by climate change, particularly by increased water temperature and reduced  
472 vertical mixing, which are two processes that are known to influence the population dynamics  
473 of cyanobacteria.

474 Recently, Tariku and Gan (2018), modeled the impacts of climate change on the  
475 extreme precipitation indices and temperature of the River Nile Basin and indicated that the  
476 extreme precipitation indices are projected to increase in the second part of this century.  
477 Similarly, Thiery et al. (2016) projected that LV will be a hotspot for heavy thunderstorm

478 events in a future with warmer climate scenarios. These changes might have dramatic  
479 consequences on LV because extreme rain events contribute to runoff and soil erosion, which  
480 enhance the eutrophication of aquatic ecosystems (e.g., Moss et al., 2011) and consequently  
481 the occurrence and intensity of cyanobacterial blooms (e.g., Michalak et al., 2013).

482

## 483 **5. Consequences of cyanobacterial blooms on the different uses of the lake**

### 484 *5.1 Consequences on food resources and fishing*

485 Fishing is an important food resource for approximately 1.5 million people living on the lake  
486 shores as well as for the 42 million inhabitants in the watershed of LV. In this context,  
487 cyanobacterial blooms have two main impacts on the fish communities: (i) the changes in the  
488 environmental conditions of the fish due to the blooms, with potential negative impacts on the  
489 abundance and diversity of the LV fish community, and (ii) the accumulation of cyanotoxins  
490 in the fish and the associated risks for the human populations consuming those fish.

491 It has been shown in numerous water bodies worldwide (e.g., Padmavathi & Veeraiah,  
492 2009; Lehman et al., 2010) that severe cyanobacterial blooms impact fish populations, mainly  
493 through changes induced in environmental parameters such as dissolved oxygen  
494 concentrations. Indeed, severe anoxia is recorded at the bottom of deep lakes or throughout  
495 the water column in shallow lakes due to the high respiration activity of bacteria degrading  
496 organic matter produced by cyanobacteria. In LV, several studies have linked water quality  
497 degradation to eutrophication and the changes occurring in the fish communities. For  
498 instance, Kundu et al. (2017) reported significant differences in the fish community structure  
499 in the Nyanza Gulf, where severe cyanobacterial blooms are frequently observed, and just  
500 outside of the gulf where better water quality occurs. Furthermore, Kolding et al. (2008)  
501 examined the relationship between the deterioration of water quality and the decline of Nile  
502 perch in the lake. They hypothesized that the low oxygen concentrations at the bottom of the

503 lake resulting from the degradation of phytoplanktonic organic matter may be the cause of the  
504 decline in Nile perch. However, this hypothesis is still in debate, as discussed by Mkumbo &  
505 Marshall (2015).

506 The second impact of cyanobacterial blooms on fish communities is associated with  
507 the potential accumulation of cyanotoxins in the fish and their subsequent potential  
508 consequences on human health. Based on laboratory and field studies in several countries, it is  
509 known that MC can accumulate in fish tissues (e.g., Jiang et al., 2012; Nchabeleng et al.,  
510 2014). In LV, three studies (Semyalo et al., 2010; Poste et al., 2011 and Simiyu et al., 2018)  
511 have shown the accumulation of MC in several fish species. The extent of MC accumulation  
512 displayed considerable variability (from 0.5 to 90  $\mu\text{g}\cdot\text{kg}^{-1}$  wet weight) among the fish species.  
513 For the highest toxin concentrations, the estimated daily exposure to MC could exceed the  
514 tolerable daily intake (TDI) proposed by the WHO for chronic exposure from fish  
515 consumption (i.e., TDI of 0.04  $\mu\text{g}$  MC-LR per kg body weight per day) (Ibelins and Chorus,  
516 2007), especially for *Haplochromis* spp. and *Rastrineobola argentea* (Silver fish), which are  
517 consumed whole. With the growing cage aquaculture in the B&Gs of LV and the incidence of  
518 increasing nutrient loading from aquaculture, cultured fish could accumulate cyanotoxins, but  
519 no data are available. Consequently, all these data suggest that the consumption of fish from  
520 LV could significantly contribute to the chronic exposure of human populations to MCs.

521

## 522 *5.2 Consequences of direct water use and water supply*

523 As shown in Table 1, the MC concentrations in the LV water frequently exceed 1  $\mu\text{g}\cdot\text{L}^{-1}$ ,  
524 which is the threshold proposed by the WHO (Chorus and Bartram, 1999) for drinking water,  
525 and sometimes exceed 10  $\mu\text{g}\cdot\text{L}^{-1}$ , which is the lowest threshold set by the sanitary authorities  
526 from the northern countries for recreational activities (Chorus et al., 2012). Consequently, as  
527 emphasized by Kotut et al. (2006), these MC concentrations in the B&Gs are now a real

528 challenge for local water authorities. However, regular monitoring of the MC concentrations  
529 in the lake water and in the treated water produced by the plants located in the B&Gs is not  
530 regularly performed. Moreover, there is no information on the sanitary risks for people  
531 directly using lake water for domestic activities, including cooking and washing, or for  
532 recreational activities during bloom events.

533 In addition to the potential threat of cyanobacterial blooms to human populations  
534 through the consumption of raw or treated water or contaminated fish, these blooms have  
535 direct and indirect consequences on the price and quantity of drinking water produced by the  
536 treatment plants. In Uganda, Oyoo (2015) showed that cyanobacterial blooms impacted the  
537 price of the water in different ways. First, a clarification stage was added to the oldest water  
538 treatment plant (Gaba I) to improve the water quality. Second, the dosage of aluminum sulfate  
539 used in the plants increased three times from 1993 to 2008 due to the increasing prevalence of  
540 cyanobacterial blooms, and prechlorination was introduced to enhance coagulation and  
541 settling (Olokotum, 2017). Third, the cyanobacteria blooms in Murchison Bay have forced the  
542 water supply authorities and institutions to establish a new water treatment plant outside of  
543 the bay at Katosi (Damba channel), which will incur additional costs due to the construction  
544 of a long pipeline to carry the treated drinking water to the Kampala metropolitan area.

545 In addition to the increasing costs of water treatment due to cyanobacterial blooms,  
546 Oyoo (2015) reported the impacts of cyanobacterial blooms on the availability of water to  
547 local populations. The increased frequency of backwashing to avoid clogging of the sand  
548 filters during water treatment at Gaba I & II in Kampala decreases the runtime of the  
549 machinery, which consequently decreases the quantity of water produced by the plants for  
550 populations. The costs of production and the availability of treated water are very important in  
551 developing countries because when the price increases and/or the availability decreases, the  
552 local populations tend to use alternative water resources that are not safe for their health (Moe

553 and Rheingans, 2006).

554 Finally, from all these data, Figure 4 shows the potential health impacts of  
555 cyanobacterial blooms for human populations living around LV. Concerning the health  
556 impacts of cyanotoxins, limited data demonstrates their real adverse effects on human  
557 populations. However, due to the high recorded MC concentrations and the potentially high  
558 exposure of humans to these toxins (in comparison to populations from developed countries),  
559 these impacts on human health should be seriously considered. This hypothesis is supported  
560 by the recent paper of Roegner et al. (2020) showing that the health of peri-urban fisher  
561 communities in the area of Kisumu is threatened by the consumption and use of lake water  
562 contaminated with MCs and other HAB components. Moreover, in addition to the  
563 disturbances caused by cyanobacteria during the production of drinking water, human  
564 populations can also consume nontreated water from the lake or poorly treated water with  
565 potential exposure to fecal pathogens associated with waterborne diseases.

566

567 **Figure 4.** Potential impacts of cyanobacterial blooms on human health in Lake Victoria

568 LW: Lake water; DW: Drinking water

569

## 570 **6. Efforts to reduce eutrophication and the occurrence/intensity of cyanobacterial** 571 **blooms**

572 Knowing that it is well established that the eutrophication of freshwater ecosystems promotes  
573 cyanobacterial blooms, the reduction of external nutrient inputs in the lakes is the main  
574 sustainable strategy to reduce cyanobacterial blooms (e.g. Huisman et al., 2018). LV is a very  
575 complex socioecological ecosystem, and there is limited documented knowledge (and  
576 understanding) regarding the social and ecological dynamics and interactions involving LV.  
577 However, based on existing knowledge, we provide arguments for the eutrophication



578 trajectory of LV and the necessity to carry out ambitious and sustainable management  
579 measures to address this major problem. The modeling approach developed by Downing et al.  
580 (2014) shows that controlling eutrophication is key to the protection and restoration of LV  
581 and its ecosystem functions and G&S. This finding is shared by many scientists as well as the  
582 local and international authorities in charge of the management of LV. Over the past 10 years,  
583 many actions have been taken to restore LV under the authorities of the East African  
584 Community (EAC), Lake Victoria Fisheries Organization (LVFO), Lake Victoria  
585 Environment Management Program (LVEMP), and Nile Basin Initiative (NBI) (Kayombo  
586 and Jorgensen, 2006).

587         We have attempted to differentiate the issues affecting the B&Gs and the OL resulting  
588 from population growth and human activity because (i) the B&Gs are more polluted than the  
589 OL and (ii) the main sources of pollutants affecting these areas are different. The pollution of  
590 the B&Gs is largely due to the discharge of (i) solid and liquid wastes/pollutants originating  
591 from big cities located on their banks and (ii) sediments and nutrients from the intensive  
592 agricultural farmland. Consequently, efficient wastewater collection and treatment of these  
593 domestic and industrial pollutants are critical in reducing the hyper eutrophication of the  
594 B&Gs. In Murchison Bay (Uganda), most of the influxing nutrients are carried by the  
595 Nakivubo channel (Fuhrimann et al., 2015), comprising mainly the rainwater and the  
596 domestic and industrial wastewater of Kampala (Matagi, 2002; Kayima et al., 2008). With  
597 this goal in mind, the Kampala Capital City Authority (KCCA) launched the Green Industry  
598 Campaign in 2016 with the goal of improving wastewater treatment (KCCA, 2018). Recently,  
599 the KCCA also piloted a new action plan to improve fecal sludge collection and transport  
600 from household pit latrines, which are common in Kampala suburbs (KCCA, 2017). Finally,  
601 the construction of a new wastewater treatment plant in Kampala (Bugolobi/Nakivubo sewage  
602 plant) should increase the sewage treatment capacities of the National Water and Sewerage

603 Corporation (NWSC), which oversees water sanitation in Uganda. Similar approaches have  
604 also been implemented for Kisumu located near the Nyanza Gulf in Kenya and for Mwanza  
605 located near the Mwanza Gulf in Tanzania in the framework of the Lake Victoria Water  
606 Sanitation Projects (LVWATSAN), which were first launched in 2004 but still continue to  
607 support actions for the improvement of solid and liquid waste management  
608 (<https://unhabitat.org/the-lake-victoria-water-and-sanitation-project/>).

609 All these actions are very important for the protection of the B&Gs of LV, but  
610 estimating their “real” impacts on the improvement of the water quality in the B&Gs remains  
611 difficult. Indeed, in urban areas, the wastewater collection networks are still limited, which  
612 results in the treatment of a small proportion of sewage, and with the predicted increased  
613 population growth rate (2 – 5% annually), sewerage production will increase.

614 In addition to improving wastewater collection and treatment, the protection and  
615 restoration of the numerous wetlands that are associated with the B&Gs is also important. As  
616 discussed before, many wetlands have been degraded due to the pressures linked to  
617 population growth. Consequently, several projects in the three riparian countries around LV  
618 focused on the rehabilitation of natural wetlands and the construction of artificial wetlands.  
619 These programs are aimed at securing and maintaining the hydrological and ecological  
620 integrity of wetlands (MWE, 2018). This initiative requires active involvement and  
621 participation of the local communities living in these areas, as shown in Kenya by Raburu et  
622 al. (2012) and in Uganda by Wacker et al. (2016).

623 Concerning the OL, it has been shown that in addition to river discharge, aerial  
624 depositions are the main source of nutrient inputs in the lake (e.g., Tamatamah et al., 2005;  
625 Kayombo & Jorgensen, 2006). Therefore, a reduction of these inputs would be associated  
626 with an integrated approach for the protection of the catchment area, including better soil  
627 cover management and improved land use patterns (Okungu & Opango, 2005; Vuai et al.,

628 2013). To adequately protect the watershed, deforestation needs to be halted and forests need  
629 to be restored; this constitutes a much greater challenge due to the complexity of the drivers  
630 of this phenomenon (Masese et al., 2012; Waiswa et al., 2015). These authors also note the  
631 absolute need to involve local communities in all these processes.

632 In the framework of the Lake Victoria Environmental Management Project phases I  
633 and II (LVEMP I and II), several soil conservation and afforestation projects were  
634 implemented to limit soil erosion and the aerial deposition of nutrients in the lake. The impact  
635 of these projects on the water quality of the OL has not been estimated. However, considering  
636 the size of the watershed and the increasing population density, soil conservation projects will  
637 require considerable concerted efforts by the five countries before expecting “significant  
638 changes” in the water quality of the main lake.

639 In interaction with LVEMP projects, national management plans have also been  
640 implemented in the countries belonging to the LV watershed. In Kenya for example, a master  
641 plan for the conservation and sustainable management of water catchment areas was proposed  
642 in 2012 by the Ministry of Environment and Mineral Resources (MEMR, 2012). Sub  
643 catchment management plans have been implemented, for example for the Awach Kano,  
644 leading to reduced deforestation, water pollution, gully erosion, etc. (Nyanchaga and Openji,  
645 2017). In Tanzania, similar catchment-based actions have been implemented for the  
646 protection of LV in the framework of Integrated Water Resources Management and  
647 Development (IWRMD) plans (Domasa, 2019).

648

## 649 **7. Conclusion**

650 Due to the demographic growth and the rising concentration of the population into urban  
651 areas in Africa (United Nation, 2018), we may fear that in the next decades, eutrophication of  
652 freshwater ecosystems and associated cyanobacterial blooms will continue to increase in LV

653 and also in many other African lakes. Knowing that all these lakes provide numerous  
654 ecosystem G&S and are vital for the water and food supply, the high microcystin  
655 concentrations recorded in water and fishes of LV and the data of Roegner et al. (2020)  
656 suggest that cyanobacteria and their toxins constitute a serious health concern for local  
657 populations. The same is probably true in many countries of the intertropical area in Africa.  
658 Consequently, it is becoming urgent in Africa (i) to implement long term monitoring  
659 programs of cyanobacteria and cyanotoxins in lentic freshwater ecosystems, (ii) to define  
660 water policies and rules for cyanobacteria and cyanotoxins and to inform human populations  
661 about sanitary risks and (iii) to take actions for reducing the exposure of human populations to  
662 cyanotoxins knowing that among these actions, the provision of affordable and easily  
663 available treated-water is an urgent priority.

664 In a longer-term perspective, the battle against eutrophication will be one of the great  
665 challenge of African countries. As shown in this review, the three main axes in this battle will  
666 concern (i) the wastewater treatment and management in urban areas knowing that currently  
667 available treatment methods might not be used in Africa due for example, to the lack of  
668 appropriate structure (Wang et al., 2014), (ii) the promotion of a sustainable agriculture, such  
669 as conservation agriculture, allowing to provide foods to a growing population whilst  
670 minimizing environmental impacts (Giller et al., 2015) (iii) the protection and restoration of  
671 wetlands, which can play a very important role in nutrient retention and reduction, even for  
672 great lakes (Watson et al., 2016) .

673 As already experienced in developed countries, all these actions for reducing the  
674 exposure of human populations to cyanotoxins and the eutrophication will be very costly and  
675 consequently require international financial cooperation. There is also need for international  
676 collaborative research programs involving scientists and people from local institutions

677 working in the water domain. Finally, the involvement and participation of the local  
678 communities will be also a key factor for their successful development.

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1170 **Supplemental Table 1.** Dissolved nutrient and chlorophyll-a concentrations in the Lake  
1171 Victoria

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1173 **Supplemental Figure 1.** Chlorophyll-a and microcystin concentrations in the main lake and  
1174 in the bays and gulfs of the Lake Victoria

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1176 **Supplemental Figure 2.** Population size dynamics in the five countries of the watershed of  
1177 Lake Victoria (data from the “World Population Prospects, The 2017 Revision”, United  
1178 Nations; <https://population.un.org/wpp/Download/Standard/Population/>)

1179

1180 **Supplemental Figure 3.** Geographical distribution of the human population densities in the  
1181 Lake Victoria watershed.

1182