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Traces of Eutrophication in Winam Gulf, Lake Victoria

The bays of Lake Victoria have experienced a steady eutrophication throughout the past decades. One of the most obvious consequences of this eutrophication is the intensive proliferation of water hyacinths (*Eichhorna crassipes*) along their shores, and in particular in the Winam Gulf (or *Nyanza* Gulf). Native to the Amazon, this aquatic weed is a popular ornamental plant in ponds worldwide, and a rapid invader when released into nature.

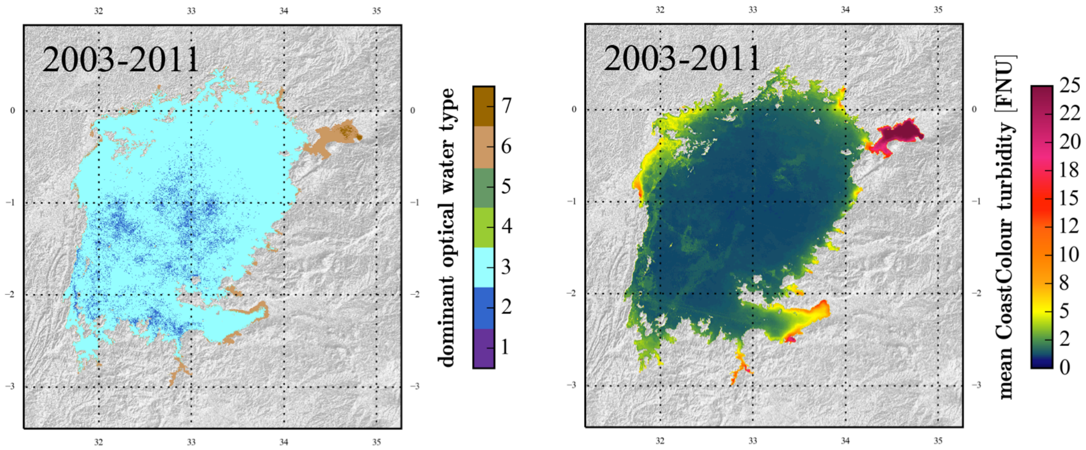
Water hyacinths were first spotted in Lake Kyoga in May 1988, and arrived in the Winam Gulf by 1990 from the Kagera River (Albright et al., 2004; Gordon et al., 2009). Due to the abundance of space, nutrients and illumination, their high reproduction rate and the lack of natural enemies, a massive accumulation in many beaches and bays resulted, most notably in the Winam Gulf. The weed carpets have several negative socio-economic and environmental effects. They disrupt fishing activities, transport, irrigation and water purifycation, provide a breeding ground for carriers of human diseases, and affect biodiversity.

Mechanical removal of invasive water hyacinths on the Ugandan shore of Lake Victoria, 1998 (image courtesy of Conver BV, The Netherlands).

Hydrology, climate and environmental pressure

Lake Victoria is at 1135 m a.s.l. and by area the second largest fresh water lake in the world, at 69'485 km^2. Its shoreline is shared by Kenya (6 %), Uganda (45 %) and Tanzania (49 %). It lies in a shallow depression between the Great Rift Valley and the western Albertine Rift, and has an average and maximum depth of 132 m and 265 m, respecively. The lake receives 85% of all water input from precipitation, and only 15% from several small tributaries. Similarly, evaporation accounts for 85% of all water loss, and only a minor output is through its only outlet, the Victoria Nile in the north. The lake's surface level varies by up to 3 m, mostly in response to rainfall, to a smaller extent due to managed outflows (Awange and Ong'ang'a, 2006). Pelagic waters in Lake Victoria are stratified, seasonally variable and receive nutrients mainly through diffuse atmospheric deposition (Njiru et al., 2012).

Winam Gulf is a 1400 km^2 large bay with a 550 km shoreline located entirely in Kenya, in the northeast of Lake Victoria. It is connected to the main basin only by the 3 km wide Rusinga channel. An even narrower, but deeper channel south of Rusinga Island used to allow for better circulation, but was closed by a causeway built in 1980. Average and maximum depth in the Winam Gulf are 6 m and 68 m, respectively. The physico-chemical conditions in the Winam Gulf are very unlike those in the pelagic area of the main basin. The water is too shallow to be persistenly stratified, and the four major tributaries entering the Winam Gulf account for 37.6 percent of all surface water inflow into the whole of Lake Victoria, including large amounts of terrigenous constituents. Agriculture and fertilization are extensive in the area around the Winam Gulf. Main cultivation periods are from December to February and July to September. An increase in sedimentation and nutrient content in the gulf due to land degradation, surface run-off and soil erosion has been observed throughout the past decades, while a proposed increase of atmospheric deposition remains disputed (Gordon et al., 2009).



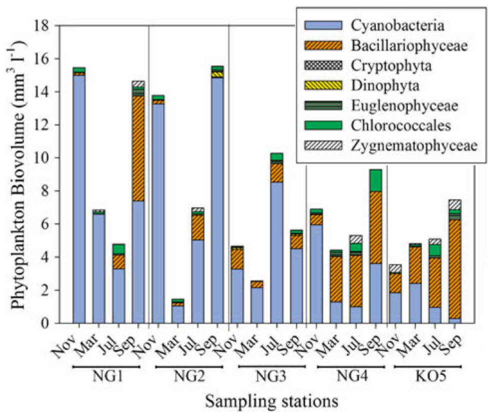
9-year aggregates of MERIS derived optical water types (left) and turbidity (right) in Lake Victoria. The relatively clear water in pelagic areas is classified as type 3 and 2. On the contrary, several bays are classified as type 6 or 7 and exhibit high turbidity, most significantly Winam Gulf in the northeast (basemaps from NASA SRTM).

Succession of aquatic communities

During the *El Niño* rains of 1998, dense carpets of water hyacinths expanded across the Winam Gulf (Albright et al., 2004; Okongu et al., 2005). Mechanical, chemical and biological approaches for their removal were piloted, among which biocontrol by weevils (*Neochetina eichhorniae* and *N. bruchi*) was found most effective (Gordon et al., 2009; Williams et al., 2007). Nevertheless, an even more extensive expansion occurred during the *El Niño* rains of 2007, with a maximum extent of 440 km^2 around April 24, after several years of moderate variability (Fusilli et al., 2013). Proliferation of water hyacinths is not only favoured by eutrophication, but further deteriorates water quality. First of all, they form a dense surface coverage that reduces the exchange of oxygen between air and water, and prevents surface mixing. Second, the coverage shades the water body and thereby prevents regular phytoplankton growth. And third, they produce a large amount of organic matter whose decomposition significantly increases the biological oxygen consumption. In addition, water hycianths affect the breeding and the juvenile feeding of many fish species.

Up to the late 1980, phytoplanktivorous and detritivorous haplochromines cichlids constituted the highest number of species and biomass in Lake Victoria. The invasive Nile perch, an apex piscivore which constitutes 80% of all fish biomass today, fed at that time mainly on haplochromines until their near decimation, and then switched to invertebrates and *R. argentea*. Between 1997 and 2010 the number of haplochromines recovered and became again more prominent in Nile perch diet. This strict control of phytopoanktivorous and detritivorous populations by the invasive Nile perch favours algal production and detritus sedimentation, and is therefore another cause for deep water hypoxia. Besides this, there is also evidence that hypoxia may foster tolerant native species such as catfishes, lungfish and tilapia (Njiru et al., 2012).

In the course of eutrophication, phytoplankton biomass in terms of chlorophyll-*a* has increased to more than the ten-fold between 1961 and 1990 (Prepas and Charette, 2005). The diatoms previously dominating the phytoplankton community were succeeded by more nutrient-loving species including toxic cyanobacteria (Sitoki et al., 2012).



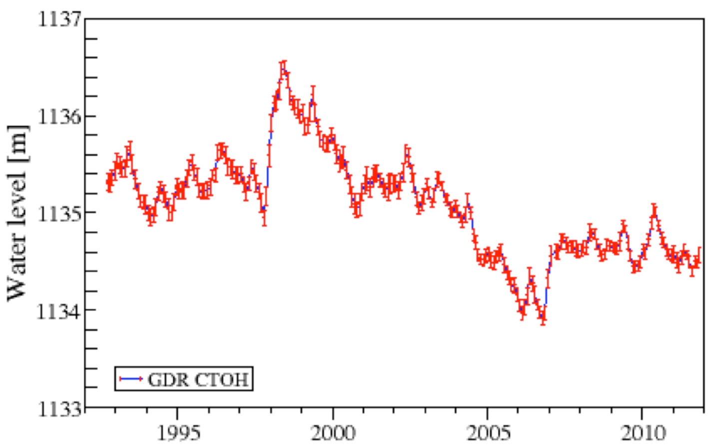
Phytoplankton classes sampled in 4 locations across Winam Gulf, east (NG1) to west (NG4), and one west of Rusinga Island (KO5), between Nov. 2008 and Sep. 2009 (from Sitoki et al., 2012).

Water hyacinth expansion and retreat

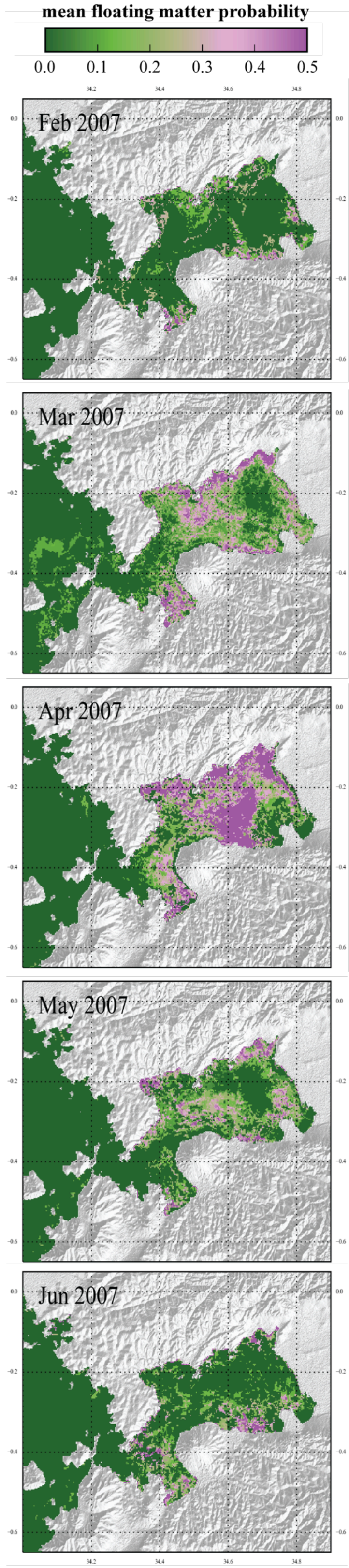
Earth observation is undoubtedly one of the most suitable techniques to assess the large-scale extent of floating vegetation, whereas several different approaches were demonstrated (Cavalli et al., 2009; Cheruiyot et al., 2014; Fusilli et al., 2013). The Diversity II floating vegetation and floating cyanobacteria probability products indicate the fraction of corresponding observations in each month. This type of product does not reveal the instantaneous extents visible in individual acquisitions, but gives an indication of the overall spatio-temporal presence of floating matter.

The course of the extreme hyacinth proliferation in 2007 in the Diversity II floating matter estimates agrees well with the findings in Fusilli et al. (2013). The event coincides with a significant lake level increase recorded by radar altimeters, which holds also for the 1998 event. Inside the Winam Gulf, the floating matter is identified as cyanobacteria dominated due to the cyanopigments in the water surrounding the hyacinths. For this reason, the image sequence on the right consists of the sum of floating vegetation and floating cyanobacteria. In March 2007, water hyacinths are even detected past the Rusinga channel. These patches are correctly classified as floating vegetation rather than floating cyanobacteria, as the background phytoplankton is predominantly eucaryotic in this area. Extensive patches of floating matter are also mapped along the northern shore of Lake Victoria, again with maximum extents in 2007. In and off Kadimu Bay however, the abundance has steadily increased until 2010.

Aiming to provide multiple water quality parameters for hundreds of lakes worldwide, the Diversity II processing chain applies a generic method for the separation of land and water. This approach is challenged by very dense floating vegetation, which is identified as solid ground and remains unconsidered. In consequence, floating material is generally underestimated for open water areas in the Winam Gulf. Continuously and densely covered areas such as the eastermost bay in Winam are even completely omitted.



Water level fluctuations in Lake Victoria from radar altimetry (from LEGOS Hydroweb, www.legos.obs-mip.fr/soa/hydrologie/hydroweb/).

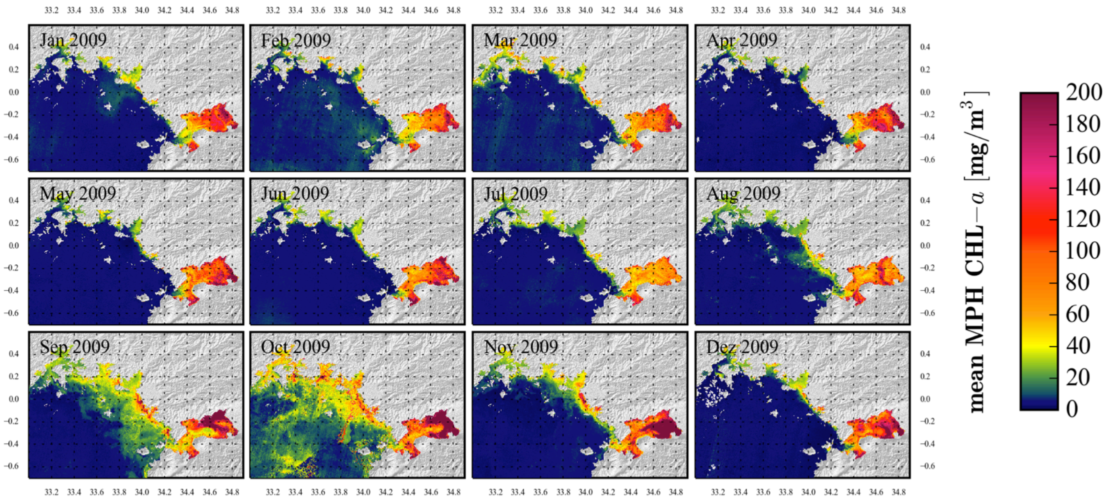


Course of the intensive water hyacinth proliferation in Winam Gulf in the first half of 2007.

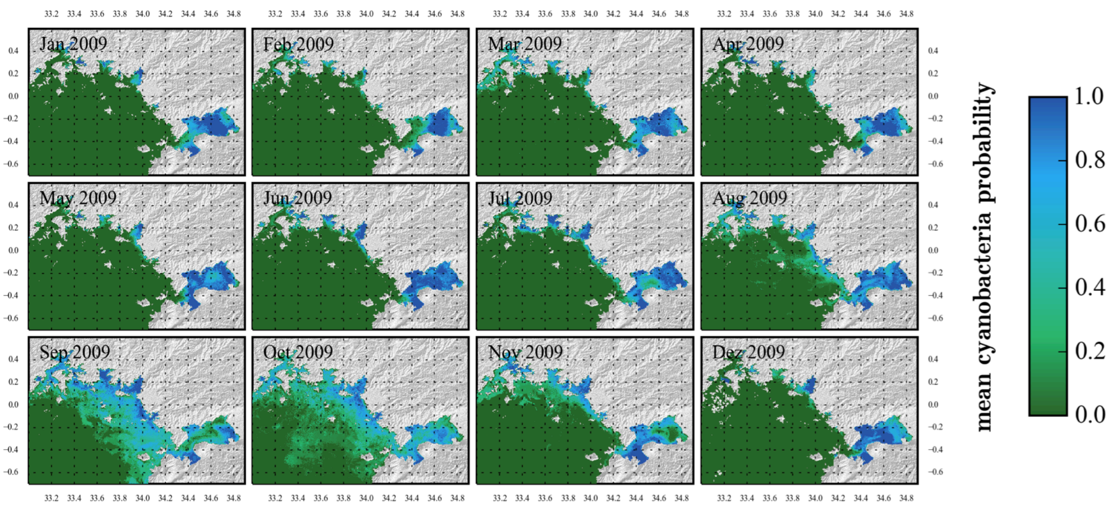
Abundance and composition of immersed algae

The increasing eutrophication and abundance of cyanobacteria reported in Sitoki et al. (2012) are confirmed by Diversity II satellite retrieved chlorophyll-*a* and cyanobacteria probability products. The Winam Gulf has extraordinarily high chlorophyll concentrations throughout the year. Most other bays along the northern and northeastern shore are less affected but still subject to eutrophication, with constantly high chlorophyll levels. In contrary, algae abundance in the oligotrophic offshore areas increases only in September and October. The dimension of this annually occurring event is considerable in terms of both spatial extent and chlorophyll concentrations, although a calibration of the FUB chlorophyll concentrations with reference data would be required to provide accurate absolute values for the latter. Atmospheric deposition is however an unlikely driver for these events, as the predominant wind direction over Lake Victoria is south.

The cyanobacteria probability maps show that Winam Gulf is almost permanently dominated by cyanobacteria. Cyanobacteria occur also during the September and October algae blooms in offshore areas, but are only dominant in about a tenth of all satellite images acquired during those months.



Monthly chlorophyll-*a* variability in Winam Gulf and neighbouring offshore areas, 2009. The MPH product is appropriate for the turbid water types in the Gulf, but less reliable offshore. However, the more appropriate FUB chlorphyll estimates for the same months confirm the temporal variations in pelagic areas, at lower absolute values.



Monthly cyanobacteria probability variability in Winam Gulf and neighbouring offshore areas, 2009. The probability includes both floating and immersed cyanobacteria. They prevail in most eutrophic areas and occur even offshore during the algae blooms in September and October.

Conclusions

The increased nutrient supply to the Winam Gulf and other bays, and the rapid proliferation of water hyacinths give clear distinction to the spatio-temporal dynamics in Lake Victoria. The 2002-2013 time series provided in the Diversity II database document the presence of these environmental drivers in agreement with other sources, including in particular the 2007 response to the *El Niño* rainfall. They demonstrate the potential of Earth observation to monitor long-term trends, and to assess the local impact of eutrophication beyond directly affected areas.

The phytoplankton growth dynamics observed in pelagic areas seem to be too extensive and are out of place to be the result of atmospheric nutrient deposition only, but further investigations using meteorological data and possibly atmospheric turbidity would be required to make a conclusive statement. Furthermore, detailed fish count data are needed for a comparison of water quality and the occurrence of distribution of turbidity tolerant native species on one hand, and the relationship between food supply and the emergence of phytoplanktivorous and detritivorous cichlids on the other hand. However all relevant water quality parameters are subject to strong spatial gradients, while seasonal variability is considerably more prominent in offshore areas.

Further reading

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