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# Groundwater contamination by sewage causes benthic algal outbreaks in the littoral zone of Lake Baikal (East Siberia)

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ABSTRACT

Lake Baikal, an ancient lake in Siberia, contains more endemic species than any other lake in the world with most of them residing in the benthic littoral zone. Explosive growth of benthic *Spirogyra*, a filamentous green alga, began approximately in 2011 in localized coastal areas, with the most severe examples occurring near coastal towns that lack a wastewater treatment facility or have a malfunctioning system. At other sites (small settlements, harbors), however, the cause of its excess growth is less obvious. Multiple hypotheses have been offered including lake level fluctuations, climate warming, a relaxation of grazing pressure, and coastal eutrophication. We assessed these hypotheses using data on historical lake levels, water temperature, the spatial-temporal distribution of *Spirogyra* along inhabited and non-inhabited shorelines, and measurements of fecal coliform bacteria and nutrients in ground water, interstitial water, and lake water. These data suggest that groundwater contamination is the primary cause of coastal eutrophication. Most houses and buildings in small settlements around Lake Baikal lack septic tanks but use unlined cesspools to collect human waste. This untreated human waste enters groundwater via passive filtration through permeable soils and flows to the coastal zone where it drives excess growth of *Spirogyra*. Remediation — including installation of septic systems, modernization of existing sewage treatment plants in coastal towns, and the adoption of non-phosphate containing detergents — as well as a reconsideration of the federal monitoring system regarding the coastal zone is urgently needed to protect this extraordinary lake.



## Introduction

Anthropogenic eutrophication (excess nutrient enrichment from human activity) is one of the major problems afflicting lakes, rivers, and the ocean world-wide (Millenium Ecosystem Assessment, 2005). The vulnerability of freshwater ecosystems to anthropogenic eutrophication and the recovery of many of them following nutrient reduction by diverting sewage effluent or implementing advanced wastewater treatment have been investigated for nearly 6 decades (reviewed by Smith and Schindler, 2009). Notably, however, much of this research has focused on eutrophication of the water column. Yet, the benthic zone of coastal areas, particularly of large, oligotrophic lakes, may be the 'first responder' to nutrients entering from land-based activities (Rosenberger et al., 2008; Schneider et al., 2014). In such lakes, inordinate amounts of nutrients would be necessary to eutrophy the large water column, but relatively smaller fluxes of nutrients to the substrate of the littoral zone could promote excess growth of benthic plants (Barton et al., 2013; Lambert et al., 2008).

Lake Baikal, the world's largest lake volumetrically, contains more endemic species than any other lake with most of these unique species residing in the benthic littoral zone (Timoshkin, 2011). Explosive growth of benthic *Spirogyra*, a filamentous green alga, began approximately in 2011 in localized coastal areas of this lake (Timoshkin et al., 2016) with the most severe examples occurring near coastal towns that either lack a wastewater treatment facility or have a malfunctioning system allowing excess nutrients to enter nearshore areas (Khodzher et al., 2017; Kravtsova et al., 2012, 2014; Timoshkin et al., 2016; Tomberg et al., 2017). At these sites, riverborne nutrients entering the coastal zone cause concentrations in nearshore waters to exceed background levels by as much as 20–60 fold (Khodzher et al., 2017; Tomberg et al., 2017).

At other coastal sites (small settlements, harbors) the cause of excess growth of *Spirogyra* is less obvious. At such sites, groundwater

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contaminated with nutrients may enter the substrate of the coastal zone and promote growth of *Spirogyra*. Indeed, results of hydrological research conducted in temperate zone lakes show that groundwater inputs often occur close to lake shorelines and decrease with distance offshore, but exceptions exist (Rosenberry et al., 2015). Groundwater can be a significant source of nutrients in oligotrophic lakes (Lewandowski et al., 2015), contributing to eutrophication (Meinikmann et al., 2015). Most investigations of the biological response to seepage and groundwater-born nutrients (particularly phosphorus and nitrogen) in lakes have focused on macrophytes, and these studies show enhanced biomass (Frandsen et al., 2012; Lodge et al., 1989), increased growth (Frandsen et al., 2012), and altered chemistry of leaf tissue (Sebestyen and Schneider, 2004). In contrast, the response of near-shore benthic algae and epiphytes to groundwater-born nutrients has seldom been investigated, but existing studies also show increased algal biomass (Hagerthey and Kerfoot, 1998; Périllon et al., 2018) and altered species composition (Hagerthey and Kerfoot, 2005).

In this paper, we use data on the spatial-temporal distribution of *Spirogyra* along inhabited and non-inhabited shorelines in Lake Baikal and measurements of fecal coliform bacteria and nutrients in groundwater, interstitial water, and lake water to answer the question: Does groundwater contaminated with human sewage and associated nutrients trigger excess growth of benthic *Spirogyra* in coastal areas? In addition, we argue that warming waters associated with climate change, lake level fluctuations, and a relaxation of grazing pressure are, alone or together, unlikely to be the major drivers of the observed *Spirogyra* outbreaks. We conclude with management recommendations aimed at curbing excess growth of *Spirogyra* in nearshore waters.

## Methods

Historically, the western coast of Lake Baikal has been investigated more thoroughly than the eastern coast, and therefore the former will be used predominantly as the model site for understanding the distribution of *Spirogyra*. Sampling localities are shown in Fig. 1.

### *Spirogyra* sampling

Benthic algal sampling occurred, generally from June–October in 2013–2016, mostly along the western coast of Lake Baikal and around two islands, Ol'khon and Bol'shoi Ushkani Island (Fig. 1). Two dominant morphotypes of *Spirogyra* were identified in areas of its mass development (Figs. S1–S4), and their wet biomass (g $m^{-2}$) were quantified along transects (10–15 m long) perpendicular to the coastline at water depths of 0.5–1.5 m using quadrat sampling and the stone-unit method (Nakashizuka and Stork, 2002; Timoshkin et al., 2015).

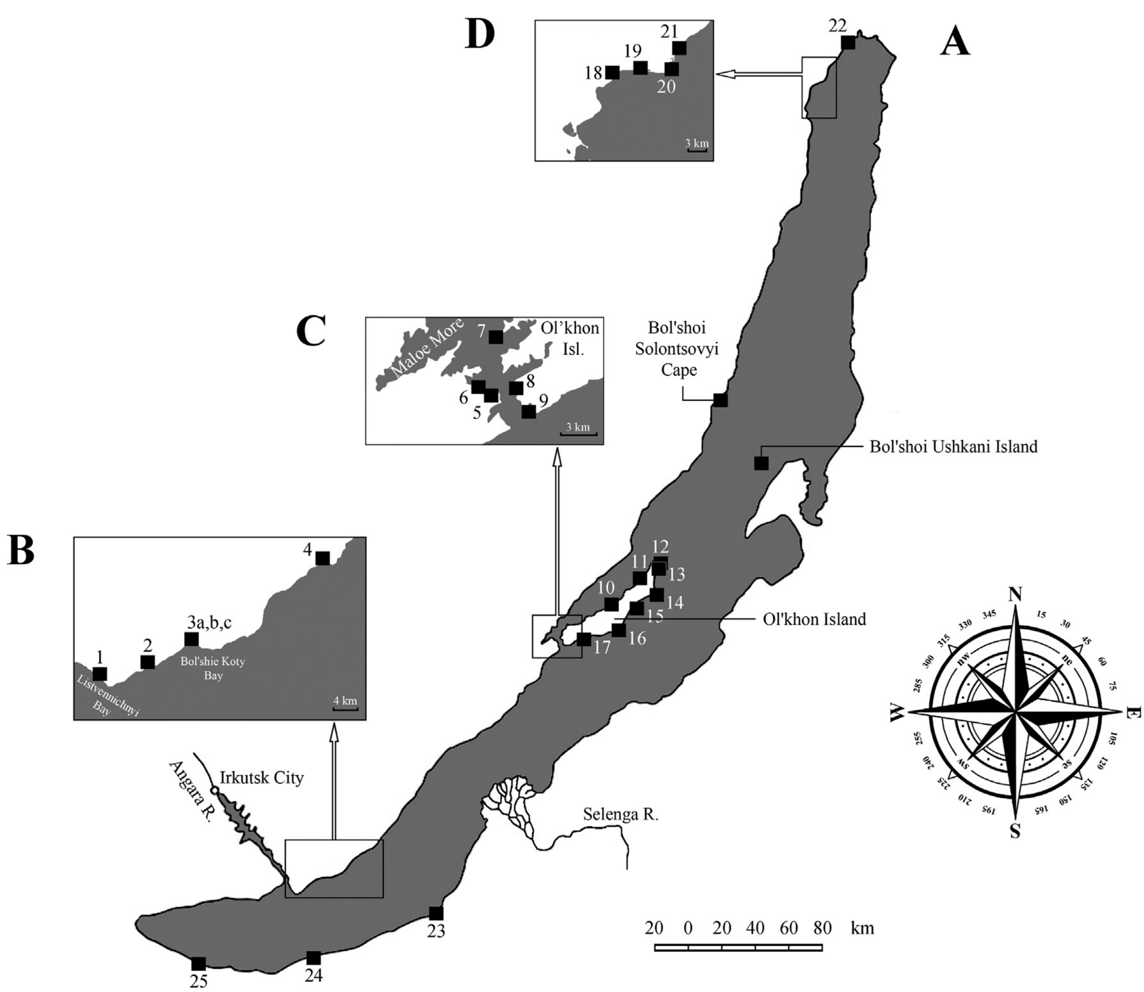


**Fig. 1.** Map of Lake Baikal with sampling localities: 1 — Listvyanka Settlement, 2 — Emelyanikha Bay, 3 — Bol'shie Koty Settlement and Bay (a, Chyornaya Stream; b, Zhilishche Stream; c, Bol'shaya Kotinka Rivulet), 4 — Bol'shoe Goloustnoe Settlement, 5 — Tutaiski Bay, 6 — Sakhyurte Settlement, 7 — Kharin-Irgi Cape, 8 — Perevoznaya Bay, 9 — Ushun Bay, 10 — Khuzhir Settlement and Shamanka Bay, 11 — Zantyk Cape, 12 — Khoboi Cape, 13 — Shunte Levyi Cape, 14 — Izhimei Cape, 15 — Khara-Khushun Cape, 16 — Ukhan Cape, 17 — Khalzyn Cape, 18 — Senogda Bay, 19 — Zarechnoe Settlement, 20 — Tyya River mouth, 21 — Severobaikal'sk City, 22 — Nizhneangarsk City, 23 — Babushkin City, 24 — Tankhoi Settlement, 25 — Baikal'sk City. The Limnological Institute's Field Station (LFS) is located within the Bol'shie Koty Settlement and Bay between 3b and 3c in inset map B.