

Review

Potential Impacts of Induced Bank Filtration on Surface Water Quality: A Conceptual Framework for Future Research

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Abstract: Studies on induced bank filtration (IBF), a cost-effective and reliable drinking water production method, usually focus on processes affecting the target drinking water quality. We aim to expand this view by assessing potential impacts of IBF on surface water quality. We suggest that IBF can directly and indirectly affect several physical, chemical and biological processes in both the sediment and open water column, eventually leading to positive or negative changes in source water quality. Direct effects of IBF comprise water level fluctuations, changes in water level and retention time, and in organic content and redox conditions in littoral sediments. Indirect effects are mainly triggered by interrupting groundwater discharge into the surface water body. The latter may result in increased seasonal temperature variations in sediment and water and reduced discharge of solutes transported by groundwater such as nutrients and carbon dioxide. These changes can have cascading effects on various water quality, e.g., by facilitating toxic phytoplankton blooms. We propose investigating these potential effects of IBF in future field and laboratory studies to allow for more detailed insights into these yet unknown effects and their magnitude in order to assure a sustainable application of this valuable technique in the future.

Keywords: drinking water; groundwater; macrophytes; lake; river; sediment; surface water-groundwater interaction

1. Introduction

Bank filtration (BF) is the process by which surface water infiltrates into aquifers. BF occurs when the hydraulic head in the surface water is higher than in the adjacent groundwater. This may naturally be the case, for example in lowland rivers or during high water stages, or caused by groundwater abstraction from wells next to the surface water, a process which is referred to as induced bank filtration (IBF, Figure 1). A stream, lake or river which is subject to BF is also termed a losing stream/lake/river, but water bodies may also be losing in some reaches and gaining in others [1]. It is not uncommon that groundwater abstraction in the vicinity of surface waters leads to unintentional BF, which will be included in the following discussion.

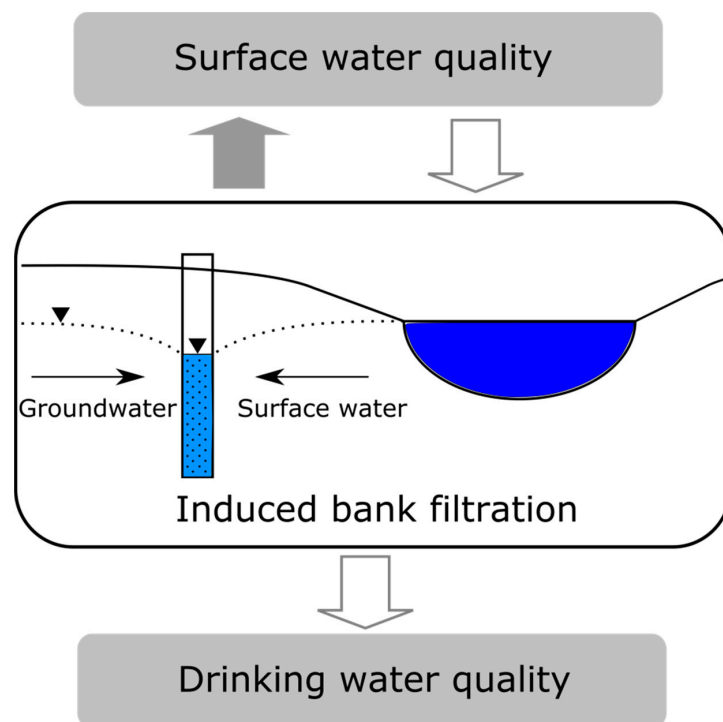


Figure 1. During induced bank filtration surface water from a source water body (dark blue) infiltrates into the sub-surface and reaches the groundwater well (light blue with dots). Traditionally, research focused on the effects of surface water and bank filtration on drinking water quality and quantity (unfilled arrows). We propose to include the neglected effects of bank filtration on surface water quality (filled arrow) into research to secure sustainable drinking water supply and sufficient ecological quality of source water bodies.

Anthropogenically induced riverbank filtration (RBF) and lake bank filtration (LBF) are alternative ways to assure a potable water supply in sufficient quality and quantity [2]. Other managed aquifer recharge methods are ponded infiltration and soil-aquifer treatment [3]. During IBF suspended solids, bacteria, viruses, parasites or adsorbable or microbially degradable water constituents are partially or fully eliminated (e.g., [4]). IBF has also been recommended as a treatment against odour problems in drinking water gained from surface water [5]. While it is generally widely acknowledged that IBF is a beneficial pre-treatment option for drinking water production, knowledge about its effects on lake and river ecosystems is very limited. Although more than half of the 524 available papers (Web of Science topic search using “bank filtration”, June 2018) have been classified into Environmental Sciences (Figure 2a), none focuses on the effects of IBF on lake or river ecosystems (one exception being Jacobson et al. [6] that deals with effects on fish habitats). Instead, research concerning IBF has almost exclusively dealt with its purification efficiency as well as infiltration capacity, maintenance considerations and other engineering issues (e.g., [2,4,7,8]). This is surprising, as the source water quality is of high importance for securing high drinking water quality and quantity (Figure 1). In the case of negative effects of IBF on surface water quality, toxic cyanobacteria blooms could occur or be worsened, which would increase the risk of toxin contamination in drinking water even after IBF [9,10] and the need for chlorination [11]. Phytoplankton blooms also increase sedimentation and thus lower hydraulic conductivity and, thereby, the infiltration of surface water into the groundwater [12]. In addition, redox conditions in the sub-surface, which are also affected by surface water quality, can result in increased concentrations of dissolved iron, manganese, hydrogen-sulphide and ammonium in drinking water [4]. We argue that IBF indeed can affect surface water quality and knowledge about this interaction is needed to secure an optimal and sustainable application of this drinking water

production technique in the future, avoiding the abandonment of IBF sites as happened in Europe in the last decades [13].

The aims of this study were to (i) assess the extent of IBF usage and the types of surface water bodies potentially affected by IBF by carrying out a literature study on case studies worldwide and to (ii) hypothesize on plausible indirect and direct effects of IBF on surface water bodies in order to (iii) develop a conceptual framework for future research assessing these effects.

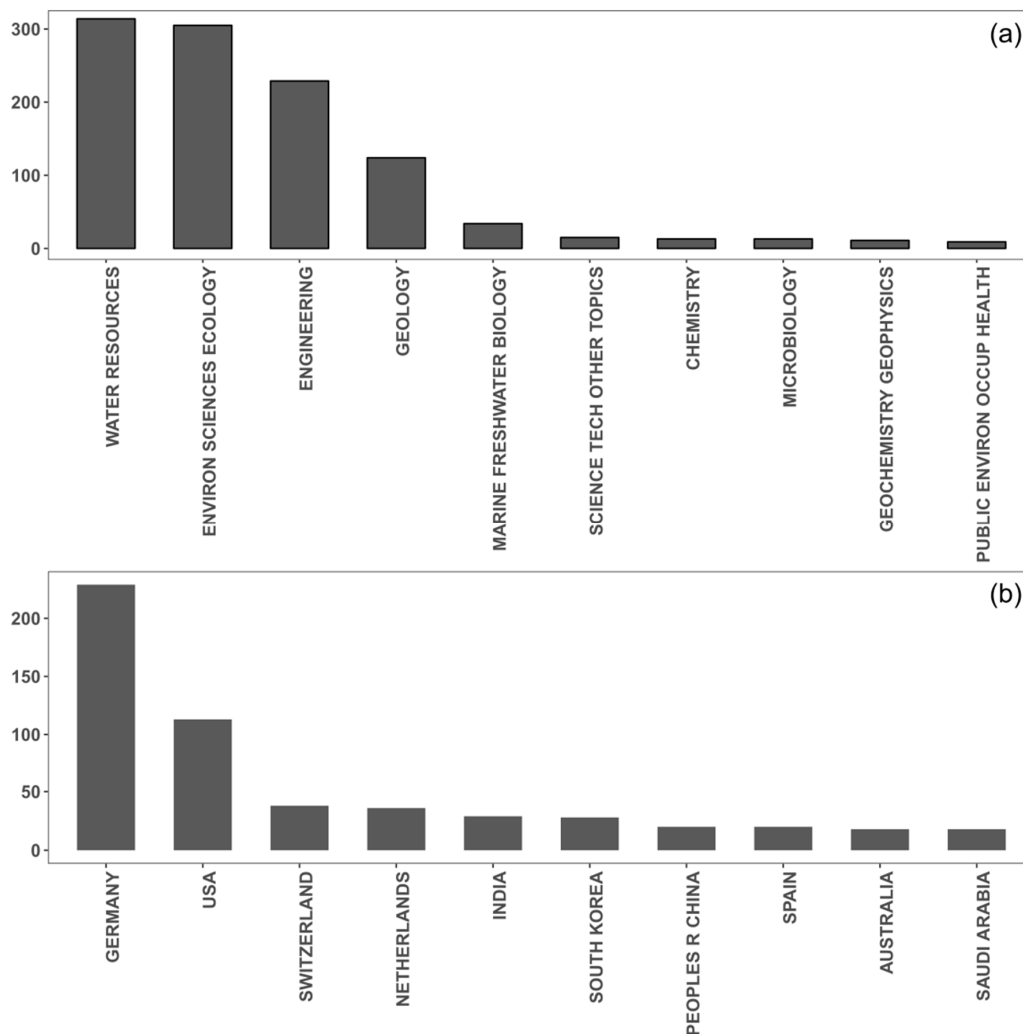


Figure 2. Top 10 studies in the categories research area (a) and countries/regions (b) of papers available on bank filtration (Web of Science topic search “*bank filtration”, June 2018).

2. Use of Induced Bank Filtration (IBF) and Source Surface Water Bodies

2.1. Worldwide Use of IBF and Affected Surface Waters

IBF has been used for more than 100 years and at present is a widely applied method in many European regions [13–15] (Table 1). Drinking water derived from infiltrating river and lake water provides a significant share of potable water supplies in various European countries (Table 1). It is also used in North and South America and Asia (Table 1). IBF is not yet utilized in many developing countries, although feasibility studies have been carried out in for example Malawi and Kenya [16].

Table 1. Percentage of induced bank filtration (IBF) in drinking water supply of different countries/cities and source surface water bodies. The symbol “ means same as above, * indicate that info is missing, - that info is not applicable.

Country	City	Percentage of Drinking Water Provided by IBF	Source Water Bodies	River Discharge, Lake Volume/Size	Reference
Austria	*	*	River Enns	65–206 m ³ /s	[17]
"	Innsbruck	*	River Inn	730 m ³ /s	[18]
"	Vienna, Linz	*	Danube	1900 m ³ /s	[19]
Bulgaria	*	*	*	-	[19]
Finland	Kuopio	*	Lake Kallavesi	4730 million m ³	[20,21]
"	*	*	Not mentioned	*	[9]
France	Paris region	*	Seine River	450 m ³ /s	[22]
Germany	-	9 to 16	-	-	[23,24]
"	Berlin	60	-	-	[4]
"	"	-	Lake Müggelsee	36 million m ³	[5]
"	"	-	Lake Tegel	26 million m ³	[5,25–32]
"	"	-	Lake Wannsee	15 million m ³	[5,12,27,33–37]
"	Radeburg	-	Radeburg Reservoir	0.35 km ² Max depth: 3 m	[38]
"	Düsseldorf	~100	River Rhine	2300 m ³ /s	[7]
"	Frankfurt am Main	*	River Rhine	2300 m ³ /s	[39]
"	"	*	Lower River Main	193 m ³ /s	[39]
"	Torgau and Mockritz	*	Elbe River	700 m ³ /s	[40]
Hungary	-	45	-	-	[7]
"	Budapest	-	Danube	6460 m ³ /s	[40]
"	*	-	Rivers Raba, Drava, Ipoly, Sajó, Hernád	17, 500, 21, 67, 27 m ³ /s	[41]
Italy	Lucca, Pisa, Livorno	(300,000 inhabitants)	River Serchio	46 m ³ /s	[42]
Latvia	Riga	*	Lake Mazais Baltezers	10 million m ³	[43]
"	"	"	Lake Lielais Baltezers	18 million m ³	"
The Netherlands	-	5	-	-	[7]
"	Remmerden	*	River Rhine	2300 m ³ /s	[44]
"	Zwijndrecht	*	River Rhine	2300 m ³ /s	"
"	Roosteren	*	River Meuse	276 m ³ /s	"
"	Roermond	*	Gravel pit lake De Lange Vlieter	1.2 km ² Max depth: 35 m	[45–47]
Norway	Hemne	*	Lake Rovatnet	8 km ²	[48]
"	"	*	River Buga	*	[48]
Poland	Poznań	*	River Warta	60 m ³ /s	[49]
Romania	Iasi	*	Moldova River	143 m ³ /s	[50]
Slovak Republic	-	50	-	-	[7]

Table 1. Cont.

Country	City	Percentage of Drinking Water Provided by IBF	Source Water Bodies	River Discharge, Lake Volume/Size	Reference
Slovenia	Maribor	-	Drava River	500 m ³ /s	[40]
Switzerland	-	10–30	-	-	[13,51]
UK	*	*	River Thur	40–50 m ³ /s	
Canada	*	*	Streams Wissey, Rhee and Pang	1.9, 1.25, 0.64 m ³ /s	[52]
USA	Jeffersonville	*	Lake A and B (artificial)	*	[10]
"	Santa Rosa	*	Ohio River	3512 m ³ /s	[53,54]
"	Cincinnati	*	Russian River	66 m ³ /s	[55]
"	Columbus	*	Great Miami River	109 m ³ /s	[56]
"	Galesburg	*	Scioto/Big Walnut Creek	6 m ³ /s	"
"	Independence	*	Mississippi River	16,792 m ³ /s	"
"	Kansas City Parkville		Missouri River	2158 m ³ /s	"
"	Jacksonville	*	Illinois River	659 m ³ /s	[54]
"	Kalama	*	Kalama River	40 m ³ /s	[56]
"	Kennewick	*	Columbia River	7500 m ³ /s	"
"	Lincoln	*	Platte River	203 m ³ /s	"
"	Mt. Carmel Terre Haute	*	Wabash River	837 m ³ /s	"
"	Sacramento	*	Sacramento River	660 m ³ /s	[54]
"	Cape Cod	*	Ashumet Pond	6 million m ³	[57]
Brazil	*	*	Beberibe River	0.3–0.4 m water depth	[58]
"	*	*	Lake Lagoa do Peri	36 million m ³	[59,60]
China	Matan	96	Yellow River	1839 m ³ /s	[61]
"	Baisha Town	82.1	Yangtze River	31,100 m ³ /s	"
"	Jiuwutan	82.6	Yellow River	1839 m ³ /s	"
"	Qingpu district	70–80	Taipu River	300 m ³ /s	"
"	Xuzhou	>80	Kui River	*	"
"	Chengdu	80	Yinma River	30 m ³ /s	"
India	-	*	-	-	[62]
"	Delhi	*	Yamuna River	100–1300 m ³ /s	[63]
"	Satpuli	*	East Nayar River	-	[64]
"	Srinagar	*	River Alaknanda	507 m ³ /s	[65]
"	Haridwar	*	River Ganga	1455 m ³ /s	[66]
"	Nainital	*	Lake Nainital	6 million m ³	[67]
Malaysia	Kuala Kangsar	*	Sungai Perak (river)	57 m ³ /s	[68]
South Korea	*	*	Nakdong River	37–3462 m ³ /s	[69]
Thailand	Chiang Mai	*	Ping River	287 m ³ /s	[70]
Egypt	-	0.1 (increasing)	Upper Nile	1548 m ³ /s	[71]
"	Sidfa	*	Nile	2830 m ³ /s	[72]
"	Aswan	*	"	"	[72]

Most of the published studies on IBF stem from Germany (44%) and the USA (22%, Figure 2b). Germany is the country in Europe with the most IBF sites 46 [13], but studies have been produced in a total of 57 countries (Web of Science topic search using “*bank filtration”, June 2018). According to the Federal Statistical Office of Germany [23], 8.6% of drinking water in Germany originates from IBF, while another 8.8% is defined as “recharged groundwater”, consisting mainly of intentionally recharged surface water. Schmidt et al. [24] state that around 16% of the drinking water in Germany is produced from IBF and other infiltration sites, with more than 300 waterworks using IBF and roughly 50 using artificial groundwater recharge. From a total of 56 studies on IBF mentioning its source water bodies, there were 15 lakes or ponds and 48 different rivers being used for IBF (Table 1). When IBF is conducted along large rivers, such as the Rhine or the Danube, where discharge rates are of a magnitude of $10^3 \text{ m}^3/\text{s}$ and thus much higher than groundwater influx and abstraction rates (e.g., IBF in Düsseldorf at River Rhine: 0.06% of discharge [73]), the effect of IBF on source water quality is, if not completely negligible, at least very small. In contrast, water quality of lowland rivers, ponds and lakes can potentially be affected by IBF due to their lower discharge (e.g., Lake Müggelsee: up to 50% of discharge, see below).

2.2. Example of IBF Application in Berlin (Germany)

IBF was first applied in Germany’s capital, Berlin, more than 100 years ago. For the past 70 years, bank filtration has produced approximately 60% of the city’s drinking water [4,74]. Water abstraction in Berlin occurs in around 650 wells [75] and is part of a semi-closed water cycle, where effluents from waste water treatment plants reach surface water bodies subject to water extraction via IBF for water provisioning (Figure 3). In total, 9 lakes and many reaches of the lowland rivers Spree, Dahme and Havel are affected by IBF (Figure 3).

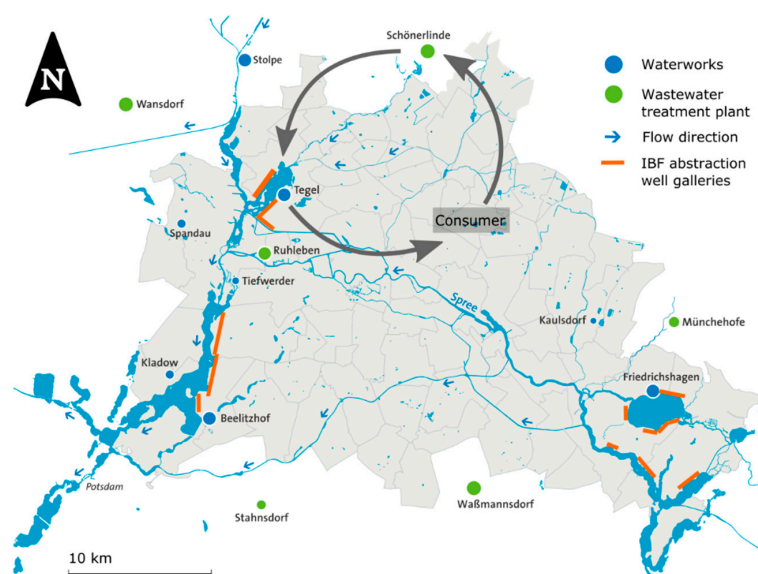


Figure 3. Bank filtration as part of a semi-closed water cycle. The water bodies of Berlin with waterworks, wastewater treatment plants and IBF abstraction well galleries, after Berlin Water Utilities [76] and Jekel et al. [77]. Most of the Berlin surface waters are part of a semi-closed water cycle where water is being abstracted via bank filtration where treated wastewater is released.

In Lake Müggelsee (Figure 4a), mean depth = 4.9 m, surface area = 7.3 km^2 [78], groundwater historically discharged into the lake under natural conditions, especially at the northern shore [79] (Figure 4c). However, groundwater withdrawal from well galleries near the shore started in 1905 [78]. Currently, IBF is performed via 170 wells located along the northern, western and southern shore (Figure 4a). Pumping rates are around 40–45 million m^3 per year (Figure 4b) distributed among the wells surrounding the lake [80], resulting in a lowering of the groundwater level of by up to 5 m

(Figure 4a,c), which is in accordance with groundwater models for the catchment area around Lake Müggelsee [79]. Zippel and Hannappel [74] calculated that 78.4% of the water reaching the abstraction wells was bank filtrate and a substantial part of the lake water was lost via IBE, with the total volume lost each year being almost equal to the volume of the lake (36 million m³ [78]).

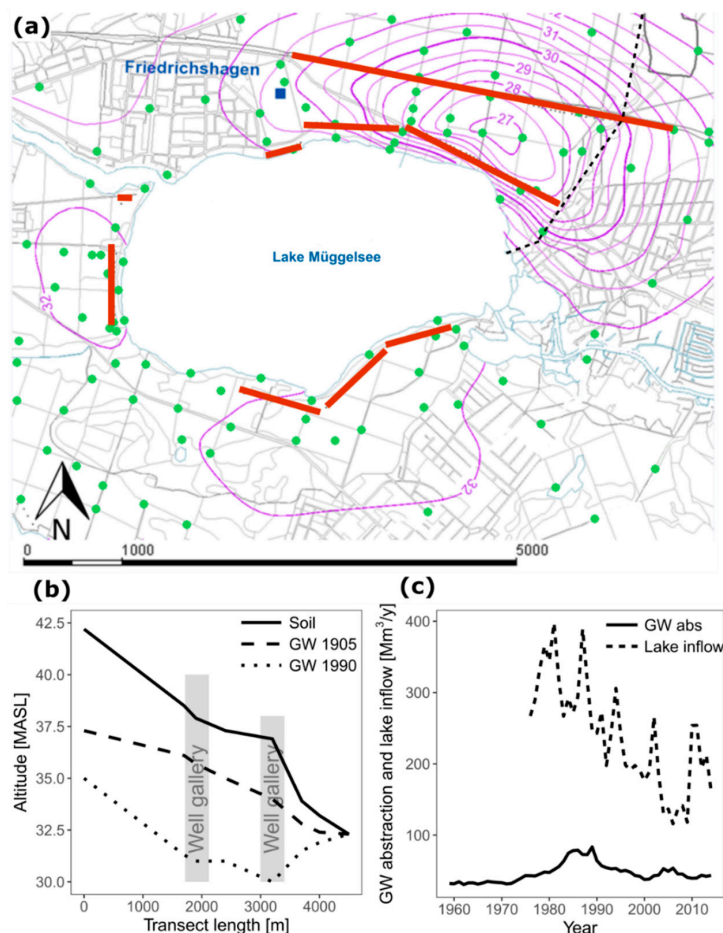


Figure 4. Bank filtration at Lake Müggelsee, Berlin, Germany. (a) Groundwater isolines for 2015 (purple lines with numbers indicate groundwater levels in meter above sea-level), well galleries with a total of 170 groundwater abstraction wells (red lines), groundwater monitoring wells (green points) around Lake Müggelsee (Germany). The transect of groundwater levels shown in panel b is indicated with dashed black line. Background map including wells provided by the Senate of Berlin, Department of urban development and housing via the FISBroker (Fachübergreifendes InformationsSystem) online mapping tool [81]. (b) Groundwater (GW) levels (MASL = meter above sea level) from 1905 (before groundwater abstraction started) and 1990 (with active pumping) along a north-south transect north of Lake Müggelsee (after Frey et al. [82]). The transect is indicated in panel a. (c) Yearly abstraction rates (solid line) of all wells surrounding Lake Müggelsee (galleries A–F) 1959–2014 [80] and surface water discharge (dotted line) into Lake Müggelsee 1976–2014 [83,84].

During the period 2014–2017 an estimated 1.1 m³/s water was extracted from Lake Müggelsee on average [80], which corresponded to about 28% of the amount of water flowing into Lake Müggelsee via the river Spree within the same period [83,84] (Figure 4b). During periods of low inflow this proportion increased and reached at least 50% on around a fifth of the days, mostly in summer. The amount of groundwater that would reach Lake Müggelsee if no abstraction took place [79] can be estimated by using the pumping rate of the northernmost well galleries (A and B) north of the lake. In the period 2014–2017 the rate was on average 0.4 m³/s [80] and in the same time period the surface water inflow to Lake Müggelsee was 3.9 m³/s [83], which means that the retention time is 10%

longer with IBF (107 days compared to 97). Longer retention times also mean a lower flushing rate of nutrients. Comparison of the nutrient retention with and without IBF using the method described by Vollenweider [85] shows that the total phosphorus (P) concentration was 9% higher with IBF (ingoing values: P load = 2000 mg/m²/year [86], discharge = 3.9 m³/s (with IBF) or 4.3 (without IBF) m³/s) compared to if groundwater would reach the lake from the north. These numbers give a first impression of potential impacts by IBF but in order to show detailed effects on lake ecology, field measurements and/or modelling are needed.

3. IBF Effects on Surface Water Quality

Induced bank filtration can potentially affect surface water bodies via two major pathways: (1) directly by induced infiltration of surface water into river and lake sediments; and (2) indirectly by preventing groundwater exfiltration into surface waters. This chapter examines potential IBF effects on physical and chemical parameters affecting biological parameters and processes and eventually surface water quality. In the following paragraphs we first describe the general effects of each respective parameter on water quality and then how IBF potentially changes the parameter.

3.1. Discharge and Retention Time

The flow regime is regarded as key driver of river and floodplain wetland ecosystems [87]. In rivers, low-flow conditions and thus degradation of rivers due to groundwater abstraction and thus unintentional BF has been detected, e.g., in Great Britain [88,89]. Similar problems are expected to be caused by IBF. Lower discharge and water levels in rivers severely change the habitat conditions for macrophytes (e.g., [90]), macroinvertebrates (e.g., [91]) and fish (e.g., [6]). Although the impacts of changes in discharge are manifest across broad taxonomic groups, ecologists still struggle to predict and quantify biotic responses to altered flow regimes [87]. We expect effects on biodiversity, macrophyte abundance, and potentially even the occurrence of harmful cyanobacteria blooms, but the effects depend on the initial conditions (Table 2). Jacobson et al. [6] used a model to show how changing pumping schedules of groundwater extraction well fields could improve the living conditions for fish in a stream by varying water extraction rates and avoiding discharge rates below certain critical thresholds for more than a limited time, thereby ensuring sufficient usable area and discharge.

Higher retention times in lakes have been reported to affect the interaction between phytoplankton and macrophytes. In shallow lakes, this interaction results in the occurrence of alternative stable states with either macrophyte dominance and clear water or phytoplankton-dominated, turbid conditions (see Section 4.2). At higher retention times, this phenomenon is more likely to occur, which has consequences for the management of the waters [92]. Higher retention times also affect nutrient retention, as shown in the Lake Müggelsee case study, where a 10% increase in retention time was estimated to cause a 9% higher total P-concentration (see Section 2.2). In summer, when natural flow is low and water demand is higher, the retention time in lakes naturally increases, hence the effect of IBF is more pronounced then.

Table 2. Potential effects of induced bank filtration on physical (WT = water temperature, RT = retention time, WL = water level) and chemical (DIC = dissolved inorganic carbon, DOC = dissolved organic carbon, pollutants such as pharmaceutical remnants and microplastics) parameters in surface waters (mechanisms: D: directly, I: indirectly due to the interruption of groundwater discharge) and examples for subsequent effects on biological parameters. The symbol “+” means that the effect will enhance the affected biological parameter, “−” that the effect will decrease the parameter, and “?” that the outcome is uncertain. The predicted effects within the parameter categories are roughly ordered according to our estimate of likelihood of occurring.

Parameter	Predicted Effect	Mechanism	References	Affected Biological Parameter	Effect	References (Example)
Physical	Higher summer WT	I	[93]	Biodiversity	±	[94]
				Macrophyte dominance	−	[95]
				Harmful blooms	+	[95]
	Lower winter WT	I	[96]	Biodiversity	?	[97]
				Macrophyte dominance	−	
				Harmful blooms	?	
	Higher RT	D, I		Biodiversity	±	[98]
				Macrophyte presence	±	[92]
				Harmful blooms	±	[99]
	Lower flow	D, I	[89]	Biodiversity	±	[87]
Macrophyte presence				±	[100]	
Harmful blooms				+	[101]	
Sediment clogging	D	[26]	Biodiversity	?	[102]	
			Macrophyte dominance	±		
			Harmful blooms	?		
Lower WL	D, I	[103]	Biodiversity	− (?)	[103]	
			Macrophyte presence	−	[99]	
			Harmful blooms	+		
Stronger WL fluctuations	D, I	[103]	Biodiversity	±	[104]	
			Macrophyte presence	−	[105]	
			Harmful blooms	?		
Chemical	Lower DIC	I	[106]	Biodiversity	±	[98]
				Macrophyte dominance	−	[107]
				Harmful blooms	±	[108]
	Lower external nutrient load	I		Biodiversity	+	[109]
				Macrophyte dominance	+	[110]
				Harmful blooms	−	[108]
	Lower DOC	I	[106]	Biodiversity	+ (?)	[111]
				Macrophyte dominance	+ (?)	[112]
				Harmful blooms	+ / −	[113]/[114]
	Lower pollutant load	I		Biodiversity	+	[115]
Macrophyte dominance				+ (?)		
Harmful blooms				?		
Higher pollutant load in the littoral	I		Biodiversity	−	[115]	
			Macrophyte dominance	− (?)		
			Harmful blooms	?		

3.2. Water Level Fluctuation

Fluctuation of the water level can be a key factor affecting the functioning of lakes (e.g., [109,116]) and rivers (e.g., [104]).

Decreasing water levels may cause former submerged habitats to be exposed to air, resulting in a loss of habitats for littoral plants and animals [117]. Groundwater abstraction was believed to have affected 151 wetland sites of special scientific interest (SSSIs) throughout England and Wales, with 100 additional wetlands perceived to be at future risk [89]. In lakes, water depth and resuspension of sediments due to wind effects are strongly linked [118]. Depending on the lake morphometry, low water levels would enable the wind at a sufficient speed to affect parts of the lake bottom that otherwise would not be affected, especially in shallow lakes. Also, a shallower depth would increase the area of the lake that may be bottom frozen, to which some macrophyte species are sensitive [97]. In

Estonia, ground water abstraction starting in 1972 caused lower water levels in three lakes, reaching a decline of up to 3–4 m in the 1980s. This led to the switch from a clear-water to a turbid state in two of the lakes, with subsequent loss of submerged macrophytes. In the 1990s the pumping decreased and the water levels were partially recovered, but the macrophytes did not return [103]. In winter, evergreen macrophytes may become partly fixed in the ice when it forms.

Water-level fluctuations may be an important trigger for the promotion of cyanobacterial blooms ([99] and references therein). In shallow lakes, water level fluctuations may trigger shifts from the clear-water, macrophyte-dominated state to the turbid, cyanobacteria-dominated state (see Section 4.2). In deep reservoirs changing water levels may result in a compressed vertical niche for macrophytes [105] and consequently reduce their inhibiting effects on cyanobacteria [119].

Induced bank filtration has the potential to decrease the water levels of inland waters or increase water level fluctuations in the case of fluctuating pumping regimes (Table 2). These effects are caused directly and indirectly by surface water infiltrating into the sub-surface and by the prevention of groundwater discharge, respectively (Table 2). Various effects of such changes on our target biological parameters have been reported (Table 2). The effects of IBF on surface water quality via effects on water level and its fluctuation strongly depend on a range of additional parameters such as lake morphology, the presence of other regulation measures for water level and background nutrient concentrations. Often, BF-induced water level changes will not be a major factor affecting surface water quality as many lakes and rivers in urban or developed regions are flow- and level regulated.

3.3. Sediment Characteristics

The purification efficiency and infiltration capacity of IBF rely strongly on the characteristics of the sediments where the infiltration of surface water takes place. Therefore, several studies have investigated clogging and redox processes at IBF sites [12,25,26,120]. Most of the purification happens within the first few meters of water transport through the sediment and the following soil layers, although the first few centimetres are already very important for the IBF performance ([14] and references therein) [27,33]. At Lake Tegel (Berlin, Germany), the waterworks pump 45 million m³/year from six wellfields around the lake, and two on the islands in the lake. Pumping from these wells affects hydraulic heads within an area of 50 km² [121]. Biological clogging with particulate organic matter (POM) reached down to at least 10 cm in the sediments. However, complete clogging did not occur in the sediments, probably due to microbial carbon turnover [25], feeding by detritivorous meiofauna [122] and opening of pores by wave action [26]. The result is a highly active biological zone with algae, bacteria, produced extracellular polymeric substances and meiofauna that still allows for IBF [26]. At low levels of labile organic matter content in the sediments, this process may facilitate macrophyte growth, but with increasing organic matter content the growth rate instead decreases [102]. Low redox potential also negatively impacts certain macrophytes' propagule emergence [123]. In addition, phosphorus ([124] and references therein) and toxic substances [125] can be released and lead to macrophyte decline and cyanobacteria blooms (Table 2, see also Sections 4.1–4.3). In surface waters with high sulphate (SO₄²⁻) concentrations, e.g., due to lignite mining in the catchment [126], hydrogen sulphide (H₂S) might form, which has been shown to be harmful to macrophytes [127].

The infiltration of oxic surface water can also oxidise upper parts of the sediments, especially during periods of high photosynthetic activity of primary producers in the surface water, but studies comparing sediment surface oxygen concentrations with and without IBF are mostly lacking. One exception being Bayarsaikhan et al. [128] who reproduced IBF processes in a laboratory setting and found that degradation of particulate organic carbon (POC) in the form of small pieces of leaf litter consumed almost all oxygen in the sediments.

3.4. Water Temperature

Water temperature is increasingly recognized as an important and highly sensitive driver of water quality [129]. As most biological processes are temperature-dependent, a water temperature regime change can have several consequences for aquatic organisms and their interactions. Temperature directly influences the distribution (e.g., [130–132]), predator-prey interactions (e.g., [133]), survival (e.g., [134]), growth rates (e.g., [135–138]), timing of life history events (e.g., [139,140]) and metabolism (e.g., [141,142]) of aquatic organisms in river and lake systems. Immediate effects of higher water temperatures in spring and summer are higher growth rates of primary producers and subsequent changes in their interactions which are crucial for maintaining clear-water conditions (see Section 4.3), as studied in several mesocosm experiments (e.g., [143–146]). Higher summer water temperatures also promote potentially toxic cyanobacteria blooms, which severely deteriorate water quality (e.g., [147–149]). In addition, mineralization of organic matter is fuelled by increasing temperatures and may result in a release of organic-bound P to the sediment pore water [150]. For shallow temperate lakes, Mooij et al. [95] predicted an increased probability of a shift from a clear to a turbid state due to climate change. Their model also predicts higher summer chlorophyll-a concentrations, a stronger dominance of cyanobacteria during summer and reduced zooplankton abundance.

Groundwater usually has a rather stable temperature similar to mean annual air temperatures; for example, groundwater temperatures in Germany vary between 10–12 °C [151]. This fact is often taken advantage of when identifying groundwater discharge zones in surface water by aerial or hand-held thermal infrared (IR) imagery (e.g., [152]). Groundwater infiltrating into surface waters thus has a cooling effect in summer, while it may warm surface waters in winter, as described in Sebok et al. [153]. Another example showed a 3 °C lower water temperature in summer in the part of a lake where groundwater discharged compared to other parts of the same lake [93]. In rivers, groundwater discharge can help keep certain parts free from ice in winter and provide cooling in summer, thereby providing a refuge for fish [135]. Consequently, a change from gaining to losing conditions in a river or lake will result in an increased amplitude of the seasonal temperature variations in surface waters. This may result in a loss of the temperature buffering function of discharging groundwater against surface water freezing in winter and against heating during summer. A lowering of temperatures in winter could lead to increased risk of bottom frozen lakes (see Section 3.2). The effect size on changing temperature buffering depends on the ratio between river discharge and lake volume on the one hand and the abstraction rate on the other. A large river would be less affected than a small river, while for lakes, the size is of less importance since the change would primarily take place in the littoral zone.

A full assessment goes beyond the scope of this study, but effects of IBF-induced temperature increases in summer can be similar to those of climate change-induced warming, especially for benthic organisms in the littoral zone which is highly likely to be warmer with IBF in summer due to the prevention of cold groundwater inflow. Overviews of climate warming effects on lake and river ecosystems are provided by Adrian et al. [94] and Whitehead et al. [154], respectively.

3.5. Nutrient Availability

Although groundwater often has lower nutrient concentrations than surface water, groundwater discharge has been reported as a potential source of additional nutrient (mainly nitrogen and P) loading from anthropogenic sources such as agricultural fertilizers, both in lakes [107,155,156] and rivers [157]. These groundwater-borne nutrients may facilitate the growth of all primary producers and affect their interactions ([107] and references therein), with mostly negative effects on biodiversity and macrophyte abundance (see Sections 4.1–4.3, Table 2). In oligotrophic systems, submerged macrophytes may either be supported by nutrients from groundwater exfiltration or decline due to competition from periphyton [107,158]. The process of increased nutrient loading to surface waters (eutrophication) often leads to the disappearance of submerged macrophytes [159] and shifts to the turbid state, especially in shallow lakes [160,161] (see Section 4.2), but also lowland rivers [92,162].

Lake Arendsee (Germany) receives more than 50% of its external P loads from groundwater, which significantly adds to its eutrophication [156]. Furthermore, groundwater discharge not only transports nutrients from the catchment into surface waters, but also contributes to a transport of nutrients from sediment pore waters into surface water [158]. Interrupting these loads by installing groundwater wells to induce BF could prevent these nutrients from reaching the surface water and thus contribute to a significant increase in water quality, both through a reduction of the limiting nutrient or by changing the nutrient stoichiometry. In contrast, nutrient-poor groundwater would contribute to a dilution of nutrient-rich water entering lakes or rivers from other sources. Mitigating this dilution effect by inducing BF would not affect the nutrient loading but reduce the actual nutrient concentrations. Furthermore, groundwater is often rich in Fe and Mn which can increase the P-binding capacity. Also, as noted in Sections 2.2 and 3.1, groundwater exfiltration lowers the retention time in lakes and helps flush the lake of nutrients.

3.6. Pollutants

In general, degradation of contaminants is less efficient in groundwater than in surface water sediment [163]. Antibiotics reaching the groundwater have been shown to change microbial community structure, enhance antibiotic resistance and thereby change ecological functions within the aquifer [164]. Remnants of personal care products and microplastics have been shown to accumulate in sediments [165,166] and to persist there more than in water [167,168]. This accumulation potentially increases by IBF with expected positive effects for pelagic, but negative effects for benthic organisms.

In case the source surface water contains pollutants, more of them could reach the littoral zone and its sediments through IBF, which might facilitate their degradation due to the higher bioactivity, but also change the community structure and abundance of sediment bacteria (e.g., [169]).

In cases where pollutants are transported into surface water by groundwater discharge (e.g., [170]), IBF could interrupt the groundwater flow and thereby stop pollutants from reaching surface water bodies. In cases where concentrations of pollutants are high, groundwater wells would most likely not be installed, but at low concentrations they might be. In such cases, the lake would benefit from pollutant mitigation by IBF.

3.7. Dissolved Inorganic Carbon (DIC) Availability

All aquatic plants can use CO_2 as a carbon source [171,172], and since the CO_2 concentration needed to half-saturate the photosynthesis of aquatic plants in general is approximately 6–13 times atmospheric levels [173] additional sources are needed. Most lakes of the world (87%) are CO_2 supersaturated [174] and CO_2 originates from mineralization of organic material in sediments and in the water column, from diffusion from the air but also from surface and groundwater inflow ([175] and references therein). In some cases, groundwater is the sole source of the dissolved inorganic carbon (DIC) influx to lakes ([107] and references therein) and the majority of boreal lakes are CO_2 -sustained by groundwater [175]. In tropical and temperate lakes, CO_2 supersaturation is dependent on groundwater CO_2 coming from weathering of minerals [176]. Groundwater in general often contains at least 35 times higher concentrations of CO_2 than lakes [177,178], up to 400 times higher in some cases [179,180].

Many macrophyte species have the ability to use HCO_3^- as a carbon source in addition to free CO_2 [181,182]. The use of HCO_3^- entails higher energetic costs [183]; therefore, macrophytes able to use HCO_3^- still grow faster in a CO_2 -rich environment [184]. Other species are fully dependent on CO_2 [118,185,186] and as a consequence, CO_2 availability is a factor that can control the abundance and species composition of submerged macrophytes. Maberly et al. [187] examined the macrophyte composition along a spring river stretch with a strong gradient of CO_2 concentrations dropping from 24 to 5 times the atmospheric concentration. At the headwaters, macrophyte composition was dominated by plants that rely on free CO_2 such as the moss *Fontinalis antipyretica*, whereas with lower CO_2 concentrations, the macrophyte composition changed to include more plants that are able to use HCO_3^- . Productive lakes often deplete free CO_2 in summer due to uptake by phytoplankton. In

those lakes, macrophytes depending on free CO₂ availability may be restricted to areas with a high organic carbon content in the sediment such as shallow protected bays [185,186].

In general, groundwater-borne DIC is supposed to support macrophyte growth, although few empirical studies are available. Frandsen et al. [188] showed that seeping groundwater increased the DIC supply, enhancing the growth of isoetids and to some extent elodeids inhabiting a groundwater-fed softwater lake. Low pH in spring water increased the growth of *Egeria densa* by affecting the free CO₂ concentration in the water [189].

In groundwater-fed lakes where CO₂ rich water enters the littoral zone, IBF would interrupt the added CO₂ contribution and thereby decrease the possibility for CO₂-dependent macrophytes to survive. This process has been suggested to be involved in the complete disappearance of *F. antipyretica* from Lake Müggelsee (Figure 4) during the last century [190]. An overall lower availability of DIC in the littoral zone due to IBF preventing groundwater exfiltration into the lake may eventually lead to an overall loss of macrophytes. This process may be accelerated by shading through planktonic and periphytic algae, which are able to saturate their need for CO₂ at low concentrations of free CO₂ due to their small size and effective carbon concentrating mechanisms. Consequently, they are able to grow fast, facing less competition for limiting nutrients with macrophytes [177,191].

Usually, lakes with a high abundance of macrophytes are characterized by a higher biodiversity [98], and a loss of macrophytes would thus potentially lead to a decline in biodiversity (Table 2).

3.8. Dissolved Organic Carbon (DOC)

Groundwater can contain considerable amounts of dissolved organic carbon (DOC) and be responsible for a significant share of the DOC flux into lakes and rivers ([107] and references therein). Natural DOC in shallow groundwater is mainly derived from decomposing organic matter in the soil and often colours the water yellow/brown [192]. Inputs of terrestrial DOC to surface waters have increased in many north temperate and boreal regions over the past decades [112,193]. This browning has several consequences for recipient aquatic ecosystems. The attenuation of light by coloured DOC restricts the growth of benthic primary producers [111–114]. Williamson et al. [111] also reported fundamental changes in vertical habitat gradients and food web structure in a long-term study on browning in lakes.

Humic substances pose significant challenges during the processing of drinking water supplies ranging from unpleasant taste, odour and colour, to the formation of potentially harmful disinfection by-products when subjected to raw water processing, which often includes treatment with reactive species such as free chlorine, ozone, chloramines, or chlorine dioxide [194]. Since IBF reduces or fully prevents groundwater discharge into inland waters (see e.g., example of Lake Müggelsee), it should thus reduce browning and all changes in water quality affected by it (Table 2). IBF that lowers browning is thus assumed to have a positive effect on biodiversity and macrophyte abundance, while both positive and negative effects on harmful cyanobacteria blooms due to changing light availability and stratification patterns have been reported (Table 2).

4. Summary on IBF Effects on Surface Water Quality

In this chapter we summarize the mechanisms by which IBF can affect biodiversity, macrophyte abundance and cyanobacteria blooms and explain the importance of these surface water quality parameters.

4.1. Biodiversity

Biodiversity of inland waters has been recognized as an invaluable parameter of the ecological quality of inland waters. In European Union (EU) member states, this recognition has resulted in the implementation of the EU Water Framework Directive in 2000. It represents a radical shift towards measuring the status of all surface waters using a range of biological communities rather than the more

limited aspects of chemical quality or targeted biological components [195]. In total, 297 assessment methods have been developed by 28 member states with more than half of the methods being based on macroscopic plants (28%) or benthic invertebrates (26%), with the remainder assessing phytoplankton (21%), fish (15%) and phytobenthos (10%) [196]. Jeppesen et al. [197] observed a significant decline in the species richness of zooplankton and submerged macrophytes with increasing total phosphorus (TP) concentrations in the water; while for fish, phytoplankton and floating-leaved macrophytes, species richness was unimodally related to TP, all peaking at 0.1–0.4 mg P/L.

IBF can potentially affect the diversity of all these components of the biological community via its different influences on physical and chemical parameters (Figure 5). In principle, a negative influence on biodiversity seems possible for fish via discharge reductions (see Section 3.1), for macrophytes via water level fluctuations (see Section 3.2) modification of sediment characteristics (see Section 3.3) and reduced CO₂ availability (see Section 3.7) and for fish, plants and phytobenthos via the increased temperature amplitude (see Section 3.4) (Table 2). However, IBF could also have a positive effect by reducing the loading by groundwater-born nutrients, DOC and pollutants, thereby increasing biodiversity of certain organism groups.

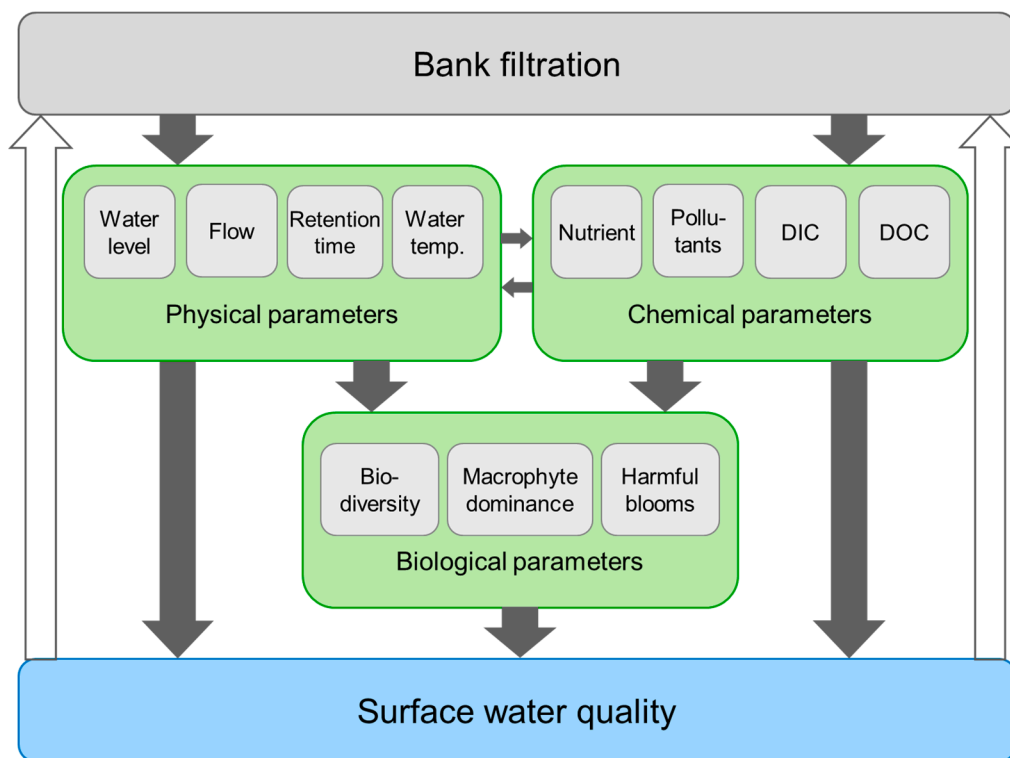


Figure 5. Conceptual scheme of potential links between induced bank filtration and relevant parameters and processes concerning surface water quality (filled arrows, DIC = dissolved inorganic carbon, DOC = dissolved organic carbon). Changes in surface water quality will in turn affect the quality of bank filtrate, which has been the focus of previous research (unfilled arrows).

4.2. Macrophyte Abundance

Submerged macrophytes play a key role for controlling water quality, both in lakes and rivers [92,160,162]. Due to a variety of stabilising mechanisms, a positive feedback between water clarity and macrophytes occurs, especially in shallow lakes and lowland rivers [92,160]. These are often either characterised by macrophyte-dominated conditions with clear water or by phytoplankton dominance and a strong risk of harmful cyanobacteria blooms. Abrupt shifts between these states can be triggered either by changes in nutrient loading or by strong perturbations of their biological

structure such as by macrophyte mowing [160,198]. Significantly positive effects of macrophyte stands on water clarity have also been shown for deeper lakes [119,199].

IBF effects on macrophyte abundance may be negative or positive (Figure 5): Macrophyte abundance may be negatively affected by a reduction of CO₂ availability (see Section 3.7) and changed redox conditions in the sediments (see Section 3.3) (Table 2). Any negative effects of IBF on macrophytes reduce their inhibiting effects on phytoplankton and thus lower critical threshold levels of shallow lakes for nutrient loading inducing regime shifts to turbid states. They would also reduce their positive effects on mineralization of organic material in the littoral sediments and thus potentially increase the risk of clogging. In contrast, there are also potentially positive effects of IBF on macrophyte abundance, e.g., in water bodies where groundwater discharge is a major source of nutrients, toxic substances inhibiting macrophyte growth, and/or coloured DOC (see Sections 3.5, 3.6 and 3.8) (Table 2).

4.3. Harmful Cyanobacteria Blooms

Cyanobacteria blooms are one of the most severe water quality problems in freshwater ecosystems, especially in lakes and reservoirs [108]. Several species of cyanobacteria produce a wide range of toxic compounds [200]. The incidence and intensity of cyanobacteria blooms and the economic losses associated with these events have increased in recent decades [147,201,202]. The abatement and control of cyanobacteria that produce toxins and create taste and odour problems in drinking water sources is a major challenge for water supplies (e.g., [5,11]). IBF has been shown potential to effectively remove cyanobacteria during underground passage [203]; however, a recent study indicates the potential for the passage of cells even for filamentous cyanobacterial species ([10] and references therein).

Several factors maintaining cyanobacteria blooms in inland waters are potentially facilitated by IBF such as lower flow, higher retention times (see Section 3.1), lower water levels (see Section 3.2), higher summer water temperatures (see Section 3.4), loss of submerged macrophytes (see Section 4.2) and the prevention of groundwater influx containing humic substances inhibiting cyanobacteria blooms (Figure 5). In contrast, the interruption of nutrient-rich groundwater discharge (see Section 3.5) and DOC to surface water by IBF may combat cyanobacteria blooms (Table 2).

5. Conclusions

IBF results in water abstraction from a variety of surface waters worldwide, including ponds, shallow and deep lakes and rivers of different discharge. Being a useful cost-effective and reliable drinking water production method, available studies on IBF only focus on the processes affecting the target drinking water quantity and quality, while its effect on surface waters so far has been ignored.

- We suggest that IBF directly and indirectly affects physical, chemical and biological processes in surface water that may have both negative and positive effects on their water quality (Figure 5). Potential adverse effects would in turn negatively affect the quality of the water abstracted for drinking water production via IBF (Figures 1 and 5). We predict that IBF-induced changes in water temperature, CO₂ availability and water retention times in lakes can lead to macrophyte disappearance, phytoplankton dominance and more suitable conditions for cyanobacteria blooms, among other consequences.
- Effects of IBF on surface water bodies are assumed to be highest in cases where discharge or lake volumes are small relative to the amount of water abstracted by IBF.
- Our conceptual impact assessment indicates the need for specific research on IBF effects on source aquatic ecosystems. While field and laboratory experiments may be suitable to test for selected processes, whole ecosystem experiments, monitoring, long-term data sets on aquatic ecosystems before and after the onset of IBF, and modelling are needed to understand the joint impact of IBF.
- Global change and urbanization are expected to increase the number of surface water bodies being used for IBF. Research on how to minimize potential negative impacts of IBF on their source surface water is thus urgently needed to ensure a sustainable use of this valuable technology.

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