Using hydrodynamic and hydraulic modelling to study microbiological water quality issues at a backwater area of the Danube to support decision-making

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Abstract  The alluvial backwater areas of the Danube are valuable ecological habitats containing important drinking water resources. Due to the river regulation and the construction of power plants, the river water levels and natural dynamics of the backwater areas continuously decline, threatening their typical characteristics. The aim of this study was to evaluate how an increased connectivity of the backwater branch located in a nature-protected riverine floodplain (enabled by diverting river water into the backwater system via a weir) affects the microbiological quality of groundwater resources. The defined quality criterion was that the diversion measures must not lead to an increased detection frequency of faecal indicators in groundwater. The microbiological water quality of the Danube, its backwater branch and the groundwater was analysed from 2010 to 2013. E. coli was selected as bacterial indicator for recent faecal pollution and C. perfringens (spores) was analysed as indicator for persistent faecal pollution and potentially occurring pathogenic protozoa. We simulated the microbial transport from the Danube and the backwater river into groundwater using a 3-D unsaturated-saturated groundwater model coupled with 2-D hydrodynamic flow simulations. Scenarios for no diversion measures were compared with scenarios for an additional discharge of 3, 20 and 80 m³/s from the Danube River into the backwater branch. While the additional discharge of 20 and 80 m³/s of Danube water into the floodplain strongly improved the ecological status according to ecological habitat models, the hydraulic transport simulations showed that this would result in a deterioration of the microbiological quality of groundwater resources. The presented approach shows how hydraulic transport modelling and microbiological analyses can be combined to support decision-making.

Keywords  Hydraulic transport model · Faecal indicators · Alluvial floodplains · Microbiological water quality · Drinking water resources

Hydrodynamische und hydraulische Modellierung der mikrobiologisch-hygienischen Qualität als unterstützendes Werkzeug beim Schutz und Management von Trinkwasserressourcen

Zusammenfassung  Die Flussauen der Donau sind wertvolle ökologische Lebensräume und enthalten wichtige Trinkwasserressourcen. Durch Flussregulierungen und den Betrieb von Kraftwerken nehmen der Wasserstand und die natürliche Dynamik in den angrenzenden Auengebieten kontinuierlich ab, was die natürliche Charakteristik dieser Landschaftstypen gefährdet. Das Ziel dieser Studie war es zu untersuchen, wie eine verbesserte Anbindung eines Auengebiets durch Einleitung von Donauwasser über ein Wehr die mikrobiologische Qualität der Grundwasserressourcen beeinflusst. Das Qualitätskriterium war so definiert, dass die Anbindungsmaßnahmen nicht zu einem häufigeren Nachweis von Fäkaliedikatoren im Grundwasser führen dürfen. Die mikrobiologische Wasserqualität der Donau und des Seitenarmes im Untersuchungsgebiet wurde von 2010 bis 2013 analysiert. E. coli wurde als bakterieller Indikator für rezente fäkal Verunreinigung gewählt. C. perfringens (Sporen) wurden als Indikatoren für persistente fäkal Verunreinigung und potenziell vorkommende pathogene Protozoen gewählt. Wir simulierten den mikrobiellen Transport von der Donau und dem Altarm im Auengebiet ins Grundwasser. Dazu
verwendeten wir ein 3-D ungesättigt-
gesättigtes Grundwassermodell, gekopp-
pelt mit einem 2-D hydrodynamischen
Strömungsmodell. Wir verglichen Mo-
dellszenarien ohne Anbindungsmäß-
nahmen mit welchen mit zusätzlichen
Einleitungen von 3, 20 und 80 m³/s von
der Donau in den Seitenarm. Während
ökologische Habitatmodelle zeigten,
dass eine zusätzliche Einleitung von 20
und 80 m³/s Donauwasser in die Au den
ökologischen Zustand stark verbessernde,
zogen die hydraulischen Transportsi-
mulationen, dass diese zu einer Ver-
schlechterung der mikrobiologischen
qualität der Grundwasserressourcen
führen würde. Der vorgestellte metho-
dische Ansatz zeigt, wie hydraulische
Transportmodellierung und mikrobio-
logische Analysen kombiniert werden
cönnen, um die Entscheidungsfindung
der Planung zu unterstützen.

Schlüsselwörter Hydraulische
Transportmodellierung · Fäkale
Verschmutzung · Indikatoren ·
Flussauen · Mikrobiologisch-
hygienische Gewässerqualität ·
Trinkwasserressourcen

1 Introduction

The wetlands of the Danube play an im-
portant role for recreation and drinking
water supply. These areas offer im-
portant habitats for rare and protected
wildlife and plant species and are part of
a national park following the Euro-
pean guidelines such as 2006/105/EG.
The groundwater bodies are important
resources for drinking water supply.
The preservation of the natural charac-
teristics and the ecological functions of
the Danube wetlands are threatened.
The elevation of the Danube riverbed
progressively declined due to the regu-
lation of river water levels through the
operation of power plants. The regu-
lation of the river has further led to
decreasing connectivity of the backwa-
ter areas. Consequently, the groundwater
levels and dynamics have declined, and
the backwater areas are sitting up,
which causes ecological deficits. The
aim of a sustainable water resource
management is thus to improve the
hydrological conditions and preserve
the ecological functioning of such ar-
reas. One possible measure is to divert
river water into the backwater branches
or to improve the connectivity of the
side branches. Such measures could
support the development of a more
dynamic alluvial backwater area with
a larger biodiversity and help preserving
the high value of the natural areas in
the long term. Such measures, however,
must be in line with the Water Rights
Act (1959) and must not lead to a re-
striction of drinking water production.
In Austria, groundwater used as drinking
water resource must have sufficient
quality to require no further treatment.
According to the Austrian Drinking Wa-
ter Ordinance (2001) and the Water
Rights Act (1959), faecal pollution is
not permitted in drinking water and
protected groundwater resources. The
compliance with this requirement is
assumed fulfilled when standard faecal
indicators are not detectable in 100 ml
sample volume.

The wetlands of the Danube inhabit
abundant wildlife including ruminants,
wild boars and birds (Arnberger et al.
2009; Frühau and Sabathy 2006; Parz-
Goliner 2006). Together with the dis-
charges of treated human wastewater
along the Danube upstream, these
sources potentially contribute to faecal
pollution of the surface water bodies.
The aim of this study was to evaluate
the impact of diverting Danube water
into an alluvial backwater area (BA, ad-
tionally to the normal influx via the
entry point during floods, Fig. 1) on the
microbiological groundwater quality
based on hydrodynamic surface water
and hydraulic groundwater modelling.
We investigated different possible sce-
narios to divert Danube water into the
study area. The investigated microbi-
ological parameters were selected ac-
cording to the Austrian Drinking Water
Ordinance (2001). E. coli was selected
as bacterial indicator for recent faecal
pollution. C. perfringens (spores) were
further analysed as indicator to include
also persistent faecal excreted patho-
gens, i.e. protozoan cysts and oocysts.
To evaluate the effect of the diversion
measures, the criterion was to achieve
no increased detection frequency of
the faecal indicators in the groundwa-
ter samples within the framework of
the standard monitoring in comparison
with the reference case of no diversion.

2 Materials and methods

2.1 Hydrological characteristics of the
study site

The study area is a typical urban river-
line wetland. It is located on the left
side of the Danube River at the border
to Vienna and is approximately 12 km²
in size (Fig. 1). The Danube is regulated
through the operation of a power plant
at the study site. Within the city’s bor-
ders, the Danube Island separates the
New Danube from the Danube. Due to
the regulation of the Danube, and the
construction of a flood protection dam
alongside the Danube, the backwater
only connects with the main stream
during sporadic high water events (see
entry point in Fig. 1). In this case,
Danube water enters the main back-
water branch at its downstream end
through a levee opening. When the
flood reaches its peak, the flow direc-
tion reverses, and the water flows back
towards the Danube River. The network
consists of numerous further partly dis-
connected side branches and isolated
ponds.

2.2 Microbiological analysis

E. coli and C. perfringens (spores) were
analysed monthly from 1-L, grab sam-
ple taken at an observation point LSW1
on the left side of the Danube from
2010 to 2012 and at observation points
LSW2–9 in the backwaters from 2010
to 2013 (Fig. 1). E. coli was further
analysed at an official bathing site of
the New Danube (ND, Fig. 1) in the
months from May to September from
2010 to 2013. E. coli and C. perfrin-
gens (spores) were further analysed in
groundwater samples at 10 piezometers
located along transects to the pumping
wells from 2010 to 2013. E. coli and
C. perfringens (spores) were analysed
following the methods ISO 16649-2
(2001) and ISO 14189 (2013). Values
reported in this paper are presented as
colony forming units (CFU)/100 mL.
At the New Danube (ND, Fig. 1), E. coli
was analysed following the method ISO
9308-3 (1998). Values are presented as
most probable numbers (MPN)/100 mL.

2.3 Groundwater flow model

For simulating the groundwater flow
and microbial transport, it was im-
portant to account for the ground-
water exchange with the Danube and
backwaters, the 3-D groundwater flow
conditions, the strongly varying topog-
raphy, the geological layers and the
unsaturated zone. Groundwater flow
and transport were simulated using
SUTRA 2.2 (Voss and Provost 2010).
The 3-D governing equation for the

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with the hydraulic pressure $p$ [kg/m$^2$], the fluid viscosity $\mu$ [kg/m/s], the fluid mass source $s$, the fluid density $\rho_w$ [kg/m$^3$], the specific yield $\theta_s$, and the water content $\theta_w$. The aquifer beneath the riverbed was 10 m deep on average and was discretized into 15 layers at an interval from 1 to 90 cm in the upper layers and 0.3 to 6 m in the lower layers. The model consisted of approximately 520,000 elements in total.

The groundwater model was calibrated by adjusting the aquifer permeability within zones and fitting the simulated to the observed hourly levels at 46 groundwater piezometers distributed within the model domain. Care was taken to consolidate the same values of permeability into large regions. The aquifer permeability was set vertically anisotropic with an anisotropy ratio of 0.1 (Eq. 1). We assumed a constant specific yield of 0.15 (de Marsily 1986). Water saturation and permeability in the unsaturated zone were calculated by using the model of van Genuchten (1980) using parameter values as obtained by the Rosetta Lite program (Schaap et al. 2001) for the sand textural class of the USDA textural class. The permeability of the confined layer was set to $1 \times 10^{-12}$ m$^2$ according to results of infiltration tests and sieve analyses. To consider clogging processes, very low permeabilities of $10^{-12}$ to $10^{-14}$ m$^2$ were assigned to the uppermost 50 cm of the riverbed and riverbank in parts of the model domain, along the bed of the main and ephemeral side backwater branches according to a manual survey (Walter Reckendorfer and Raimund Taschke, personal communication). Two calibration periods were chosen, one period during mean steady flow conditions and the other during flood events (Fig. 1), as described by Derx et al. (2013). All other vertical head boundary conditions were interpolated from measured heads at 26 groundwater piezometers located within 5 km distance. The top layer in the land zone was set to no-flow, assuming a negligible groundwater recharge from precipitation. The bottom boundary of the domain was defined to represent the aquitard. Groundwater was abstracted from five production wells. Numerical nodes that were located within a circle of 50 m in diameter around each well at the bottom model boundary represented the horizontal collector pipes extending radially at the bottom of the aquifer. Pumping rates of 330, 250, 280, 180 and 140 l/s at wells PGAW 1–5 were assumed, respectively (Fig. 1). Transient boundary conditions were set at hourly time steps. As initial pressure heads and for simulations of steady flow conditions, simulations were performed over 1.5 years holding all boundary conditions constant.

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and one period during a flood event in January 2011, corresponding to a return period of 9 years. The model calibration resulted in an aquifer permeability ranging from $1 \times 10^{-11}$ to $1 \times 10^{-9}$ m$^2$. As a measure of model performance, we calculated the Nash-Sutcliffe coefficients resulting in values above 0.87 at 78% of the piezometer locations (Fig. 2).

2.4 Microbial transport model in groundwater

We used the calibrated groundwater model to simulate the transport of *E. coli* and *C. perfringens* (spores) by solving the 3-D advection-dispersion equation with first order removal rates

$$\frac{\partial \theta w \rho C}{\partial t} + \nabla (\theta w \rho D \nabla C) + \nabla (\theta w \rho v C) = Q_i + \theta w \rho \alpha w C$$

with the microbial concentration in groundwater $C$ [CFU/100 mL], the simulation time $t$, the soil density $\rho_s$ [kg/m$^3$], the 3-D dispersion tensor $D$ [m$^2$/s], and the pore velocity vector $v$ [m/s]. The microbial removal rates [1/s] are combined filtration rates by retention and inactivation. Filtration rates of *E. coli* ranged from 0.4–2.5 l/m in sand and gravel (Artz et al. 2005; Smith et al. 1985). Using the most conservative value and a mean simulated pore velocity of $10^{-4}$ m/s during the calibration, this converts to $2.3 \cdot 0.4 \cdot 10^{-4} = 9.2 \cdot 10^{-5}$ l/s. For *C. perfringens* (spores), the same removal rate was assumed as for *E. coli*. The inactivation rate of *E. coli* in groundwater was set to 0.18 l/d (Nasser et al. 1993). For *C. perfringens* (spores), an inactivation rate of 0 l/d was assumed. According to injection tracer tests in the field, microbial transport often follows preferential flow paths (Pang 2009). To represent this behavior and to keep the numerical dispersion small, the dispersion was set so that the criterion $\nabla \cdot D \leq 2$ was met (Kinzelbach 1987), with $x$ [m] being the maximum extent of a numerical element. $D$ is the product of longitudinal and transversal dispersivity and the pore velocity $v$. In the well capture zones of PGAW 1–5, the longitudinal and transversal dispersivity were set to 20 and 1 m, respectively. A vertical anisotropy ratio of 0.1 was assumed in consistency with the sediment origin of the aquifer (Geidar et al. 1992).

2.5 Simulated scenarios

Through the combination of hydrodynamic surface water and hydraulic groundwater models, we investigated scenarios of different diversion rates into the backwater branch. The diversions were then evaluated based on the criterion that they must not lead to a significant ($p<0.05$) increase in detection rates of faecal indicators in groundwater according to the Austrian Drinking Water Ordinance (2001). One possible scenario was to pipe 3 m$^3$/s surplus water of the New Danube (Fig. 1) in free descent into the backwater branch. Additionally, we investigated scenarios to connect the backwater branch with the Danube in order to restore the natural water level dynamics. The possible scenarios included an additionally discharge of 3 m$^3$/s, 20 m$^3$/s and 80 m$^3$/s of Danube water into the backwater branch via weirs. Such measures would require substantial construction works to lower the existing traverses along the backwater river, and to widen the current entry point of the Danube during floods (Fig. 1). The transport of *E. coli* and *C. perfringens* (spores) was simulated for hydrological conditions at low water level (LW), at mean water level (MW), and at mean water level plus 1 m (MW+1) (Table 1). In all scenarios, the initial concentrations of both microbial parameters were assumed to be 0 CFU/100 mL in groundwater, which complies with the measured concentrations of faecal indicators in groundwater over 97–98% of the time (Sect. 3.1). The transport simulation time was 60 days. All simulations were run on the computer aided engineering cluster (caezserv and phoenix2.zserv, TU Wien). The computational time for each scenario was several hours.

In order to evaluate the investigated scenarios, the modelling results are presented as difference between simulated faecal indicator concentrations with and without diverting Danube water into the backwater area. These differences are presented in ranges from $10^{-3}$ to $10^{-2}$ CFU/100 mL in Figs. 4, 5, 6 and 7. An increase in faecal indicator concentrations above $10^{-2}$ CFU/100 mL would lead to higher detection rates during routine monitoring in the short term (within weeks to months), considering the frequency of standard microbiological analyses of groundwater. An increase in concentrations in the range from $10^{-3}$ to $10^{-2}$ CFU/100 mL would lead to higher detection frequencies during routine monitoring in the midterm (several months to one year). Increases in faecal indicator concentrations in the range from $10^{-3}$ to $10^{-2}$ CFU/100 mL are therefore not acceptable considering the criteria of...
3 Results

3.1 Microbiological water quality

The monitored concentrations in surface water showed similar patterns for E. coli and C. perfringens (spores). The sampling sites at the Danube revealed a moderate faecal pollution level and at the New Danube a low faecal pollution level according to the classification scheme of Kirschner et al. (2009; Tables 1 and 2). The measured values were assumed as river source water concentrations in the groundwater simulations for the scenarios (Table 1).

In the main backwater branches of the study area, the faecal contamination decreased with increasing distance from the Danube (from sampling site LSW 1 to LSW 3, Fig. 3). The observed gradient of faecal contamination correlated with the decreasing connectivity of the sampling site with the Danube (Frick et al. 2020). At the sampling sites LSW 4, 7 and 8 representing sites with little connectivity to the Danube, a high faecal pollution level was found, with 90th percentile values from 1000 to 3200 CFU/100 mL for E. coli, and from 100 to 2500 CFU/100 mL for C. perfringens (spores), respectively (Fig. 3). These elevated concentrations presumably originated from wildlife faeces. A low level of faecal pollution was found at sampling sites LSW 5, 6 and 9, with 90th percentile values ranging from 30 to 130 CFU/100 mL for E. coli, and from 20 to 200 CFU/100 mL for C. perfringens (spores), respectively (Fig. 3).

The microbiological analysis of groundwater samples in the study area (n=353) resulted in concentrations of 0 CFU/100 mL in most cases, with prevalence rates of 2.5 and 2.8% for E. coli and C. perfringens (spores), respectively. The measured concentrations reached at maximum 9 CFU/100 mL of E. coli and 16 CFU/100 mL of C. perfringens (spores), respectively.

3.2 Scenarios of increasing floodplain connectivity

A Kruskal Wallis test showed that the simulated diversion of 3 m³/s of New Danube water into the backwater branch during LW already led to a significant deterioration of the microbiological groundwater quality as compared to the reference scenario (χ²(1)=26.3, p=2.8×10⁻⁷, n=3899, Fig. 4). Higher simulated concentrations of E. coli in groundwater near the drinking water wells PGAW 1, 3, 4 and 5 in comparison with the reference case would even lead to more elevated detection rates at these sites. According to the simulations, the microbiological groundwater quality deteriorates along parts of the main backwater branch, while it improves along other parts of the main backwater branch compared with the reference scenario (Fig. 4). A similar effect was shown for C. perfringens (spores).

When diverting 3 m³/s of Danube water into the backwater branch during LW, the microbiological ground-

![Fig. 3](image-url) Observed concentrations of E. coli and C. perfringens (spores) at the observation points in the Danube (DSW 5) and in the backwater (LSW 1–9, Fig. 1) (DSW 5: n=31, LSW 1: n=33, LSW 2: n=33, LSW 3: n=34, LSW 4: n=28, LSW 5: n=31, LSW 6: n=31, LSW 7: n=14, LSW 8: n=23, LSW 9: n=29). The boxes indicate the 25th and 75th percentile, the whiskers indicate the 10th and 90th percentile, circles indicate values between the 5th and 95th percentile, horizontal lines indicate the median values.

Table 1 Microbial concentrations assumed in the backwater branches during the scenarios at low water (LW), mean water (MW), and mean water plus 1 m (MW + 1) in the Danube. The concentrations of E. coli and C. perfringens (spores) represent the 95th percentile values of the monthly monitoring data from 2010–2013

| Scenario      | Hydrological Conditions  | Source water       | E. coli CFU/100 mL | E. coli [MPN/100 mL] | n | C. perfringens (spores) CFU/100 mL | n |
|---------------|--------------------------|--------------------|-------------------|----------------------|---|----------------------------------|---|
| 0 m³/s (reference) | LW, MW + 1               | Backwater river    | 112               | 2.5                   | 95| 56                               | 95|
| 3 m³/s        | LW, MW + 1               | New Danube         | 61                | 37                    | 37| 181                              | 33|
| 3 m³/s        | LW, MW + 1               | Danube             | 330               | 33                    | 33| 181                              | 33|
| 20 m³/s       | MW                       | Danube             | 330               | 33                    | 33| 181                              | 33|
| 80 m³/s       | MW                       | Danube             | 330               | 33                    | 33| 181                              | 33|

Table 2 Classification scheme for the microbiological contamination of surface water for the faecal indicator E. coli according to Kirschner et al. (2009)

| CFU/100 mL  | Low  | Moderate | Critical | High | Very high |
|-------------|------|----------|----------|------|-----------|
| E. coli     | ≤100 | >100–1000 | >1000–10,000 | >10,000–100,000 | >100,000 |

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Fig. 4 Difference between simulated concentrations of *E. coli* with and without diverting 3 m³/s of New Danube water into the backwater area at low water level (LW) conditions (positive/negative values indicate an increase/decrease in concentrations). Indicated are the concentrations at the bottom of the aquifer after 60 days of simulation time. The same results were obtained for *C. perfringens* (spores).

Fig. 5 Representing Fig. 4 but for diverting 3 m³/s of Danube water into the backwater area.

Water quality near wells PGAW 1, 3, 4 and 5 deteriorated significantly more than if diverting New Danube water as shown by a Kruskal Wallis test ($\chi^2(1) = 938.4$, $p = 4.3 \times 10^{-36}$, $n = 5241$, Fig. 5). For all of the above scenarios, positive differences between simulated concentrations of *E. coli* with and without diverting 3 m³/s were found within the well catchment area of PGAW 1, which would therefore lead to higher detection frequencies in groundwater. Due to the higher flow rates of the main backwater branch in the scenarios than for the reference, parts of the ephemeral side branches filled up with water. Such conditions currently occur only during flood events. During MW+1, the concentrations of both faecal indicators increased even more than during LW near the main backwater branch (results not shown). The diversion of 20 to 80 m³/s of Danube water at MW likewise led to significantly increased concentrations of faecal indicators as shown by a Kruskal Wallis test in particular in the region near the main backwater branch ($\chi^2(1) = 357.4$, $p = 1.0 \times 10^{-70}$, $n = 4317$, Fig. 6, and, $\chi^2(1) = 543.7$, $p = 2.8 \times 10^{-120}$, $n = 4668$, Fig. 7). The diversion of 80 m³/s of Danube water additionally resulted in elevated concentrations of both faecal indicators near wells PGAW 4 and PGAW 5 (Fig. 7). We tested the plausibility of the model results by comparing the simulated and observed concentrations of *E. coli* at well PGW5. According to the simulations, the concentrations of *E. coli* ranged from $1 \times 10^{-2}$ to $1 \times 10^{-3}$ CFU/100 mL at well PGWA5 during MW+1 conditions (results not shown). The standard monitoring of *E. coli* at this well over multiple years showed concentrations in the same range only 3 to 5 times per year, which corresponds with the frequency in which this well is influenced by the Danube. The measured concentrations of *E. coli* at all other wells during these times were below the limit of detection corresponding with the simulation results.

### 4 Discussion

#### 4.1 Combining hydrodynamic modelling with data from standard faecal indicator bacteria

The aim of this study was to investigate the effect of diverting river water into an alluvial floodplain area on the microbiological groundwater quality as a resource for drinking water supply. The quality criteria were chosen according to the Austrian regulations for drinking water and groundwater protection (Austrian Drinking Water Ordinance 2001; Water Rights Act 1959). We addressed this question by combining faecal indicator concentrations in surface water at detectable levels with hydrodynamic and hydraulic modelling. The starting point of the microbiological water quality assessment was determined by the analysed concentrations of faecal indicators in groundwater during monthly monitoring. Then, concentrations of *E. coli* and *C. perfringens* (spores) were simulated for the
reference case, which is no diversion of river water, and compared with the diversion scenarios of 3, 20 and 80 m$^3$/s. The scenarios showed that diverting 3 to 80 m$^3$/s of Danube water into the backwater area leads to significantly increased concentrations of faecal indicators in groundwater ($p<0.05$), which would cause a higher detection rate during the standard monitoring. Already a diversion rate of 3 m$^3$/s led to higher water levels and thus to side branches filling with water, which so far only filled during flood events. Measures to divert 20 to 80 m$^3$/s of water into the backwater area would lead to increases in the water level dynamics, would homogenize the water quality and prevent the eutrophication of isolated backwater branches according to previous studies (Gabriel et al. 2014; Weigelhofer et al. 2014). Despite of this, these measures cannot be recommended from the viewpoint of groundwater as a safe drinking water resource, as the deterioration of the microbiological groundwater quality was shown to affect the drinking water well catchments. All investigated scenarios showed significantly increased concentrations of $E. \text{ coli}$ and $C. \text{ perfringens}$ (spores) in the range of $10^{-5}$ to $10^2 \text{CFU/100 mL}$ ($p<0.05$). Increased concentrations in this range would lead to higher detection frequencies during water quality monitoring programs in the short and medium term.

### 4.2 Future perspectives—linking modelling with microbial faecal source tracking and QMRA

In order to assess the safety of the drinking water resources concerning the infection protection, quantitative microbial risk assessment (QMRA) methods could be used. Further parameters to determine the origin of faecal contamination (e.g. animals versus humans) could be valuable tools to track long-term changes of the groundwater quality and to evaluate the QMRA models. These include microbial source tracking markers, bacteriophages as alternative sensitive viral indicators to detect faecal contamination, or parameters for analysing the biological stability of groundwater. Automated online techniques are becoming increasingly important to detect short time microbiological contamination as occurring during floods. Near-real time measurement techniques based on biochemical-physical online measurements are promising parameters for complementing chemo-physical online measurements as continuous process control.

### 5 Conclusion

In this study, we evaluated how an increased connectivity of a backwater branch located in a nature-protected backwater area of the Danube (enabled by diverting Danube water into the system via a weir) affects the microbiological quality of groundwater resources. While the additional discharge of 20 and 80 m$^3$/s of Danube water into the floodplain strongly improved the ecological status according to ecological habitat models, the hydraulic transport simulations showed that this would result in a deterioration of the microbiological quality of groundwater resources. The presented approach of using hydrodynamic and hydraulic modelling to study microbiological water quality issues at a backwater area of the...
based on microbiological analysis of the water resources combined with hydraulic flow and transport modelling is useful to support decision-making.

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