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REBEN

ÉDUVIZIG ÉSZAK-DUNÁNTÚLI VÍZÜGYI IGAZGATÓSÁG GYŐR

Land Burgenland

Reed Belt Neusiedler See/Fertő (Interreg AT-HU 2014-2020)

Applied hydrological and basic limnological investigations

Austrian-Hungarian Synthesis




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REBEN

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EXECUTIVE SUMMARY

Baseline situation and objectives

In 2014, a broad interdisciplinary and bilateral study was carried out under the Austrian-Hungarian Water Commission to define strategic goals for the Lake Neusiedl / Fertő region. The consortium preparing this study comprised experts from hydrology, ecology, and nature conservation as well as people from practice in various fields of ecosystem uses around the lake.

It turned out as common consensus in all fields that complex challenges with socio-political relevance can only be met on the basis of data evidence and sound scientific knowledge. A profound understanding of hydrological, chemical, and ecological interrelationships at Lake Neusiedl / Fertő is an undisputed prerequisite to provide stakeholders and politicians with the necessary basis for decisions with potentially far-reaching consequences.

Bearing this in mind, the goals of the Strategy Study were discussed and formulated. In addition, general measures to reach these goals were proposed. Finally, knowledge gaps were identified, which were considered necessary to be filled in order to deepen our understanding on the ecosystem functioning.

The project REBEN aimed at closing knowledge gaps about the processes related to the reed belt of Lake Neusiedl / Fertő. While the open lake is comparatively well described, much less is known about the reed belt, which accounts for more than half of the total area of the lake. What we do know, however, is that the extensive littoral zone is of utmost importance for the water quality and management of the lake and thus touches on some of the central goals of the Strategy Study Lake Neusiedl.

In the project REBEN, a comprehensive programme of measurements, analyses and modelling was carried out in the reed belt of Lake Neusiedl / Fertő over three years (2017–2019). The results are presented in eleven technical reports that cover the topics hydrology, physico-chemical parameters, pollutants, biological communities, reed structure, and sediment. Summarized in two national synthesis reports, these results fulfil the tasks of work package T1 of the project REBEN and form the basis for work package T2, which is to develop a joint water management plan for Lake Neusiedl / Fertő.

This Austrian-Hungarian synthesis merges the national reports of work package T1 and represents a bilaterally agreed, joint view of the key factors, driving forces and main processes in the reed belt of Lake Neusiedl / Fertő in the fields mentioned above. The aim of the synthesis is to provide an assessment of the status quo from a water management perspective as well as an evaluation of alternative scenarios considering water level and channel maintenance in the reed belt. Although based on findings at local / national level, the synthesis shall be valid for the entire lake and, hence, shall be seen as the starting point of considerations for the bilateral water management plan.

Ecosystem services

In chapter 2, we describe the ecosystem services of Lake Neusiedl / Fertő to emphasize the benefits people obtain from the lake as well as direct and indirect contributions of the ecosystem to human well-being. They are manifold and include provisioning services such as fishing and reed harvesting, regulatory services such as water quality regulation, cultural services such as ecotourism and sailing, and supporting services such as primary production. There is a straight link of the implementation of the EU Water Framework Directive to ecosystem services. The consideration of these services as well as environmental objectives, as defined in the EU Water Framework Directive, shall support a future sustainable development of non valorised goods for the next generation, but also help to avoid conflicts between contradictory interests – for the well-being of the people and the ecosystem.

Transport, processes, and loads

Chapter 3 deals with matter transport, processes, and loads which affect the water quality as well as chemical and biological processes in the reed belt of the lake. The littoral zone of Lake Neusiedl / Fertő comprises a complex mosaic of reeds and water surfaces, often along characteristic spatial gradients of water depth and reed stand density which are accompanied with corresponding gradients of physico-chemical characteristics. Our analyses revealed striking differences between areas closely connected to the open lake and isolated areas in the inner reed belt where extreme environmental conditions (*e.g.*, water temperature above 35 °C and electric conductivity above 6,000 µS cm^{-1}) can occur.

The reed belt is not only an environment of extremes but also of remarkable temporal variability. In our analyses we tried to disentangle the impacts of periodical changes of water level and air/water temperature from short term impacts due to wind setup/setdown and the accompanying *seiche* movements (standing waves) which lead to a tilting of the water level and, in consequence, currents from the open lake into the reed belt and back.

The hydrological variability was described by means of different approaches of hydraulic modelling which formed the basis for matter load calculations of suspended matter, phosphorus (as key nutrient), and selected pollutants. Apart from the hydraulic baseline conditions, water temperature, redox conditions, and pH were identified as key factors influencing the horizontal distribution and the fate of the water constituents. Based on a comprehensive programme of field measurements during several sampling campaigns, data analyses from online monitoring stations, laboratory analyses and experiments, and finally different modelling approaches, the project REBEN could significantly improve our knowledge of processes in the reed belt and especially provide quantitative data on the exchange between the open lake and the reed belt with its channels, inner pools, and extended brown-water zones.

A key outcome of the calculations in this synthesis is the estimation of sediment and phosphorus loads between the catchment area and the lake basin as well as between different compartments within the lake. Both data from REBEN and external sources were used, partly from a multi-year reliable data basis (*e.g.*, mass balance 1992–2009), partly using rough estimations and approximations. Therefore, the balance of (suspended and deposited) solids and of phosphorus should not be considered as a true balance sheet, but rather as a tool to provide orders of magnitude for the respective estimated loads. It shall help to evaluate different balance items in terms of relevance and significance.

The load calculations revealed that most of the sediment load of the Wulka (as the main tributary of the lake) settles in the reed belt near Donnerskirchen / Purbach and does not reach the open lake. The mean annual input of suspended solids contributing to steady sedimentation in this area was estimated at about 3,890 t. A significantly larger load (ca. 10,000 t per year) is formed autochthonously in the lake through precipitation of calcite (along with other minerals such as dolomite and silicates). The calcite crystals cause the characteristic turbidity of the open lake water. As revealed by field measurements and the data analyses of the online monitoring stations, the suspended solids in the open lake are transported through channels into the reed belt where they are deposited in open water areas. Removal of sediment via dredging can significantly contribute to the export of sediment from the lake basin (from marinas: 6,800 t, from channels 3,140 t per year).

The pathways of the phosphorus loads are comparable to those of the sediment loads in several aspects: a large share of the particulate phosphorus fraction entering the lake basin via the Wulka is deposited in the reed belt. However, a significant load is released again and transported as dissolved phosphorus to the open lake. Overall, the total phosphorus concentrations of the river Wulka largely reach the open lake at the edge of the reed belt though in different form. The data analyses showed that both the external phosphorus loads in the river Wulka and the concentrations in the lake are much smaller today than they were during the last extensive studies in Austria during the 1980s. During the five campaigns between autumn 2017 and spring 2019 (in total 13 sampling dates) orthophosphate concentrations (as PO_4-P) in the open lake in Austria never exceeded 5 µg L^{-1} (inside the reed belt: maximum 9 µg L^{-1}), while a concentration of more than 100 µg L^{-1} PO_4-P was found in previous studies. In channels in Hungary intermediate concentrations were found during REBEN (median of all measurements was 30 µg L^{-1}, n=151).

Among the pollutants, specific attention was paid to selected heavy metals and organic compounds (perfluorooctanesulfonic acid PFOS / perfluorooctanoic acid PFOA and fluoranthene). The analyses revealed different fates for these pollutants. PFOS is considered extremely persistent in the environment but seems to be converted to predominantly short-chain PFT as metabolites. In addition, it is eliminated from the aqueous phase of the lake by adsorption, transported to the reed belt via suspended sediments and hence removed from the lake water. In contrast, the elimination of PFOA is much less extensive than for PFOS leading to significantly higher concentrations in the lake than in the river Wulka. A relevant adsorption of PFOA on the sediments can be excluded. The fate of fluoranthene is comparable to that of PFOS, though the data indicate a potential for release from the sediment reservoir in the reed belt similar to phosphorus.

The chemical and physical characteristics of Lake Neusiedl / Fertő, which is the largest soda lake in Europe, were a main focus of the analyses in REBEN. They strongly influence the aquatic communities. Within the project, phyto- and zooplankton communities were studied at various sites both in Austria and Hungary. Specific attention was paid to the reed structure in the Hungarian part of the lake. The areal changes of the Hungarian part of Lake Neusiedl / Fertő were investigated by using archive maps of early military surveys between 1785 and 1920 and aerial photographs from 1959 to 2017. The results showed that the share of the reed area in the Hungarian part of the lake has significantly increased from ca. 25% in earlier years to ca. 83% in 1959. After the regulation of the water level in 1965, the increase of the reed area has more or less stopped (reaching ca. 86% in 2017). A detailed comparison of five designated sample sites did not reveal any significant changes between 1982 and 2017 (except those resulting from channels and dredge deposits), hence neither a sign of regeneration nor of improvement. However, a small increase of the reed area (ca. 4 ha/year) have been observed generally countrywide. In Austria, the share of open water areas within the reed belt increased from 2% in 1979 to 15% in 2008. In Hungary, special attention should be paid to the extended stands of *Schoenoplectus litoralis* (but also other submerged macrophytes such as *Potamogeton pectinatus*, *Myriophyllum spicatum* and *Najas marina*), which have increased in open water areas in the Hungarian part of the lake over the last few years.

The findings from the project REBEN are based on the experience of a few decades and the considerations for further development also concern a period that can be described as "short to medium-term". Long-term developments of the lake were briefly discussed to evaluate potential impacts on the lake. They focus mainly on the long-term accumulation of sediments resulting from the calcite precipitation and shifts in the water balance as a result of global warming.

Scenarios under different framework conditions and comparative assessment

In chapter 4 of this synthesis, we describe how the processes and load balances may change under different conditions. The considerations are based on expert assessments though founded on the extensive investigations and findings of the project REBEN. They reflect the current state of knowledge and can be regarded as educated guess.

The following scenarios are distinguished:

- Scenarios related to extreme water levels (below 115.2 m asl *versus* above 115.8 m asl)
- Scenarios related to different flow patterns of the river Wulka through the reed belt (diffuse *versus* only linear in-bank flow of the river through the reed belt)
- Scenarios related to the network of reed channels (no channels or existing channels silted up or overgrown *versus* enlargement of the existing network)

The comparison showed that the most significant impacts can be expected where exchange processes between the open lake and the reed belt are affected. This concerns mainly the channels connecting the open lake with the reed belt, which enable an effective transport of solids, nutrients and pollutants but also serve as migrating routes and habitat for fish. Scenarios where these pathways are established or supported lead to a significant export of suspended sediment and adsorbed nutrients from the open lake to the littoral zone, hence improving water quality in the open lake. The comparative analysis of the scenarios also revealed that the anthropogenic interventions in the lake have a quantitatively relevant impact: They directly influence the studied matter balances via outflow (Hanság Channel), removal (dredging) or translocation, but may also indirectly affect sedimentation processes both in the open lake (sheltered bays) and in the surrounding reed belt.

A final assessment of the status quo and possible developments under different scenarios focused on the strategic goals and objectives as defined in the Strategy Study Lake Neusiedl / Fertő. Sedimentation processes relate directly to one of the key targets: the maintenance of the ratio "open water : reed" within the lake basin. However, anthropogenic interventions on these processes (indirect or direct) are hardly compatible with the goal of allowing the system to develop and maintain undisturbed physico-chemical and biological processes – at least if we interpret this goal very strictly. This example illustrates that in none of the scenarios the requirements of all objectives of the Strategy Study are fulfilled at the same time. In some cases, they appear even contradictory. Therefore, a prioritization of objectives is needed.

It is clear that Lake Neusiedl / Fertő is not a totally natural and unaltered system anymore. It has experienced numerous impacts: from the creation of an artificial outflow (at the beginning of the 20th century) over water regulation mechanisms (in 1965 and in 2011) to significant changes on catchment area, subsequent eutrophication processes and an increasing expansion of bathing areas and marinas (second half of the 20th century). As a consequence, the lake and especially its littoral zone underwent significant changes among which the remarkable extension of the reed belt between the drying phase in the 1860s and the 1950s is the most striking one. There is little doubt that the hydrological impacts and resulting changes in the chemistry of the lake were the main factors behind the growth of the reed beds. In spite of its outstanding natural value the lake is a modified system – highly complex and highly vulnerable. This was understood early and lead to strong efforts to counteract negative trends. The efforts of the Austro-Hungarian Water Commission such as the joint weir regulation order and the reduction of external pollution from the catchment area (mainly since the 1980s) as well as the creation of a bilateral National Park in 1993 can be seen as important milestones on the way to improve and restore the ecological integrity of the ecosystem and as major contributions to a sustainable water management. In addition, comprehensive monitoring programmes were established, first by the Austro-Hungarian Water Commission, later on local and national level and during the last 20 years under the requirements of the EU Water Framework Directive. All this was done in co-operation of the two countries and involving experts and stakeholders from water management and nature conservation. It was therefore a logical consequence that the bilateral national park Neusiedler See – Seewinkel / Fertő Hanság Nemzeti Park was involved in the project REBEN as a strategic partner of the two national water management authorities.

However, there is still a lot to be done. After decades of negative anthropogenic impacts on the one hand and positive efforts and strides for improvement on the other hand, we are convinced that we should not leave the lake to its own fate. Such an approach is of course fully justified in the conservation zone of the National Park, but only there as part of the whole system. For the remaining larger part of the lake, concrete measures shall be discussed and defined on how the objectives of the Strategy Study can be reached and how the lake can maintain its ecological value as well as its potential for sustainable use. This will be the task of the Management Plan with the aim to find a compromise between different interests and objectives considering also contradictory or opposing processes involved.

1 INTRODUCTION

1.1 Baseline situation

In 2014, strategic goals for the Lake Neusiedl / Fertő region were formulated in a broad interdisciplinary and bilateral study (Wolfram *et al.* 2014). To achieve these goals, the authors proposed a total of 74 measures, 27 of them in the field of water management and 18 in the field of limnology.

Today there is a general consensus that complex challenges with socio-political relevance can only be met on the basis of sound scientific knowledge. This also applies to the goals formulated in the strategy study. The fact that these goals are in parts even contradictory documents the difficulty of bringing different interests to a consensus. It underlines even more the need for a sound technical basis for decisions for or against certain measures. To use a buzzword from the Corona crisis: measures must be evidence-based. Only on the basis of a profound understanding of hydrological, chemical and ecological interrelationships the necessary certainty for decisions with potentially far-reaching consequences can be provided to stakeholders and political decision-makers.

Compared to other waters in Central Europe, Lake Neusiedl / Fertő is a well-researched ecosystem, and with this study the authors stand on the proverbial shoulders of giants who have conducted a multitude of studies on hydrology, sedimentology, chemistry, and biology of Lake Neusiedl / Fertő since the 1960s. However, most of these studies not only provided new knowledge, but also raised new questions and sometimes led to the realization that we often only scratch the surface in our scientific endeavours. The size and complexity of Lake Neusiedl / Fertő often limit the search for a holistic and model-based understanding of the processes and dynamics of the ecosystem.

From an aquatic ecological perspective, the open lake is comparatively well described and known (Herzig & Dokulil 2001; Löffler 1979). Much less is known about the reed belt, which nevertheless accounts for more than half of the total area of Lake Neusiedl / Fertő. What we do know, however, is that the extensive littoral zone is of utmost importance for the water quality of the lake and thus touches on some of the central goals of the Lake Neusiedl strategy study (Wolfram *et al.* 2014).

The main investigations on the reed belt of Lake Neusiedl / Fertő in Austria were carried out during the 1980s (Brossmann *et al.* 1984). In Hungary studies started at the beginning of the 1960s (Tóth & Szabó 1962). Several studies dealt with the input of substances via the river Wulka (Stalzer *et al.* 1986; Von der Emde *et al.* 1986), the effects of reed cutting (Gunatilaka 1986) and the biological conditions in the reed belt (Burian *et al.* 1986; Hacker

& Waidbacher 1986). In view of the urgent task at that time – the reduction of eutrophication of Lake Neusiedl / Fertő – the focus was mainly on the reed belt at the Wulka mouth, and only rarely on other areas like Rust (Stalzer & Spatzierer 1987) or Illmitz (Metz 1984). In simplified form, the entries and conversion processes according to Stalzer & Spatzierer (1987) are as follows (Figure 1):

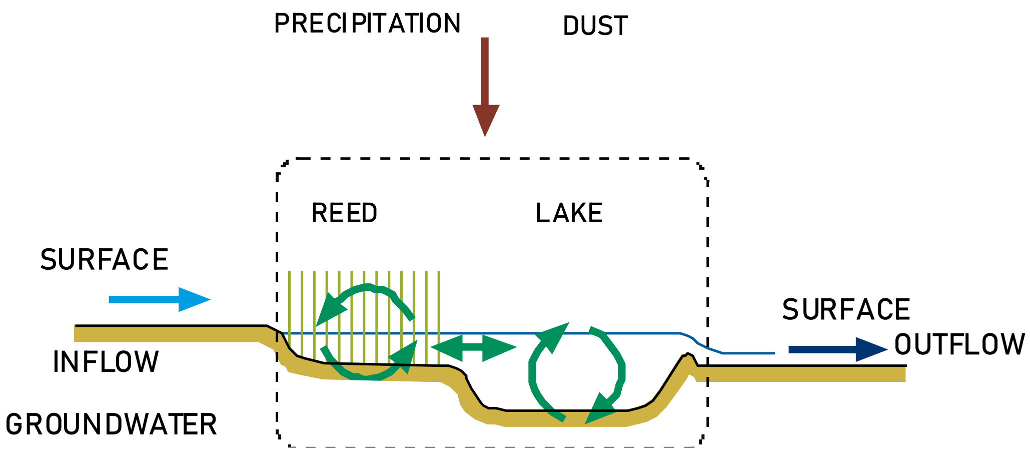


Figure 1. Scheme of inputs, outputs, and internal processes in Lake Neusiedl / Fertő. Source: Stalzer & Spatzierer (1987) (modified).

The results of the investigations from the 1980s were important for the present project already at the planning stage and provided a reference to our own findings right from the start. However, it quickly turned out that the earlier investigations were only comparable to a limited extent with the current surveys and that many of the former results could not be transferred to the current situation, on the one hand in view of changed conditions (inputs from the catchment area, flow of the river Wulka through the reed belt, overflow of the so-called lake dam), and on the other hand for methodological reasons (*e.g.*, individual sampling *versus* water quality measuring stations).

Today, the treated (C, P, N elimination) wastewater load on the Austrian side of the Lake Neusiedl / Fertő catchment area is:

- Wulka valley recipient Wulka river, indirect to Lake Neusiedl / Fertő,
- West region (Winden to Mörbisch), recipient Wulka, indirect to Lake Neusiedl / Fertő
- West region (Jois), recipient creek to Lake Neusiedl / Fertő
- North region (Neusiedl, Weiden, Parndorf) out of catchment area, recipient Leitha river, combined sewer overflows are discharge into creeks to Lake Neusiedl / Fertő
- Gols and Mönchhof, recipient Gols channel, indirect to Lake Neusiedl / Fertő,
- Illmitz region out of catchment area, recipient Hanság-főcsatorna.

The mean dry weather sewage flow that is transferred outside of the catchment amounts to about 2 Mio m³/year (as sum of dry weather sewage discharge from Neusiedl, Parndorf and Weiden; yearly averages vary between 5,000 and 7,000 m³ per day).

On the basis of Austrian investigations for the Hungarian part of the lake a nutrient balance was developed (Pannonhalmi 1984). The major input of nutrients, especially phosphorus, to the lake in the past and nowadays is the Rákos-patak, which is the main surface inflow of the lake on the Hungarian side.

In the year 1995, the sewer system for the Lake Neusiedl / Fertő southern settlements was completed and the collected sewage since that time is treated outside of the catchment area of the lake in Fertőendréd, recipient is the Ikva watercourse.

In year 2000 the design works began to reduce direct load of the lake on the Hungarian side and in 2004 two artificial wetlands were established: one for Fertőrákos (including recreation area) sewage treatment plant and one for the Rákos-patak watercourse.

After the Fertőrákos sewage treatment plant was finished, and replaced by a pumping station, from 2009 on purification of sewage water occurs in Sopron STP, recipient Ikva watercourse. The Rákos patak artificial wetland is still in operation.

The last point source pollution Balf village sewage water was connected to Sopron STP in 2014.

Since 2014, all in all no raw or treated communal sewage water loads are introduced into the Hungarian side of the Lake Neusiedl / Fertő, accordingly there is no more source for a lot of organic substances such as pharmaceutic residue.

The reeds have a canal system about 300 km long. The flow-improving reconstruction of some of them was implemented in 2014-2015 in a KEOP project.

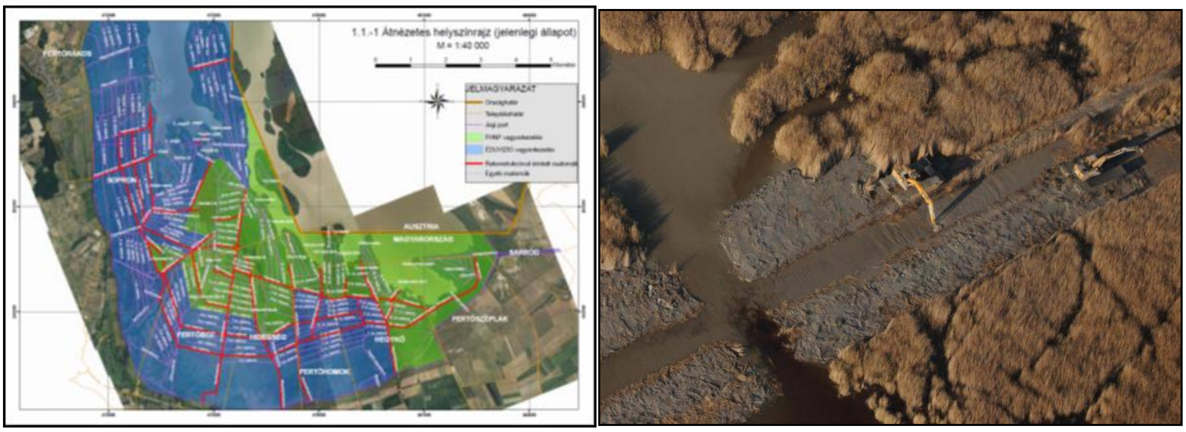


Figure 2. Canal reconstruction – 2014 (Photo: FHPNI, Pellinger A.)

The aim of the project REBEN was therefore to check older findings, but also to extend them in space and time. The project REBEN has provided new findings for the Wulka mouth as well as for the exchange between lake and reed belt far from the Wulka mouth (Mörbisch, Illmitz, Hungarian part of the reed belt). A milestone is above all the different approaches for modelling the exchange processes, which for the first time allow a quantification of lake-internal mass balances.

In the following, the project structure and the objectives of the project REBEN will be presented before the most important findings will be summarized in a synthesis in the subsequent chapters.

1.2 Project structure and objectives

1.2.1 Work packages T1 and T2

The project REBEN is divided into two **work packages**:

T1 Expert studies on topics such as hydrology, physico-chemical parameters, pollutants, reed structure and sediment

T2 Development of a joint management plan for water management at Lake Neusiedl / Fertő

Based on previous studies, the goal of work package T1 was to eliminate serious knowledge deficits and to create the necessary data basis for water management. By conducting investigations in the fields of hydrology, chemistry and biology, the knowledge about the water and mass transfer between the reed belt and open water as well as the relevance of these processes for water quality should be improved.

The detailed **objectives for the four modules** of WP T1 were formulated as follows:

Austria

Hydrology Evaluation of existing climatic and hydrographic data; supplementary installation of data collectors for pressure (water level) and temperature; measuring campaigns to measure the flow conditions in the reed belt; calculations of the water balance for typical scenarios (spatial, climatic, and hydraulic); hydraulic modelling for parts of the reed belt according to the scenarios

Chemistry/Biology *Open water:* Monitoring of general physico-chemical parameters in the water column; installation of water quality monitoring stations to characterize the dynamics

Sediment: characterization of the sediment by EEM fluorescence spectroscopy; laboratory experiments on nutrient transformation processes (redissolution, immobilization); phosphorus fractionation of the sediment

Biological quality components according to EU-WFD: Planktonic and benthic communities

Pollutants Stratified sampling in different types of reed stands and analysis of selected heavy metals and organic trace substances;
Laboratory tests for adsorption and mobilization of selected substances in the sediment; laboratory tests for biological or photocatalytic degradation of selected organic trace substances in comparison sediment and open water column; test settings over several weeks: enrichment/degradation under aerobic/anaerobic conditions and at different pH values

Reed/Sediment Investigation of sediment structure and composition depending on hydrological conditions at several dates

Hungary

The hydrological and hydrodynamic conditions of the lake were evaluated by the Budapest University of Technology and Economics (BME). The staff of ÉDUVIZIG took samples of lake water and bottom sediment, and the physical and chemistry analysis was done by Győr-Moson-Sopron County District Office, Department of Public Health, Laboratory Department, Environmental Measurement Center. The Center also sampled the phytobenthos, sampled and analysed benthic algae and evaluated the ecological status based on these data. The Centre for Ecological Research (ÖK) characterised the phytoplankton, the zooplankton and the reed-grass floating in the water or fixed to the bottom. Experts Dr. Lajos Vörös and Dr. Katalin Zsuga were subcontracted in this investigation, whereas BME commissioned Dr. Géza Király to perform the study of the reed structure.

The results of the investigations of the four modules within the WP T1 are described and discussed in detail in the corresponding **sectoral reports**. Changes in the research program were agreed with the client. For technical reasons it seemed appropriate to summarize the results in a slightly modified form in the following sectoral reports:

Austria

Report 1 Hydraulic modelling
Report 2 Reed (Processing of GeNeSee data, uses of reed)

Report 3	General physical-chemical parameters in open water and sediment; pollutants (trace substances)
Report 4	Biology
Report 5	Online measurements (water quality measuring stations) and field tests
Report 6	Laboratory tests

Hungary

Report 1	Hydrological and hydrodynamic conditions
Report 2	Test methods and evaluation of results for water and sediment samples
Report 3	Examination of phytobenthos
Report 4	Investigation of biological water quality parameters(phytoplankton, zooplankton, aquatic macrophytes)
Report 5	Investigation of reed structure

1.3 Assessment benchmark

The **present synthesis** serves as:

- the summarizing **description of the results of the WP T1**,
- the **assessment of the status quo** from a hydrological, physico-chemical, limnological and water management perspective, and
- the **evaluation of alternative scenarios** under changed conditions.

Based on the actual state (description WP T1) and the evaluation under different conditions, the synthesis leads to the water management recommendations, which are to be formulated in work package T2 (management plan).

The **assessment of the status quo** is carried out with regard to the main **water management objectives** according to the **strategy study** by Wolfram *et al.* (2014). They are summarized in Table 1 and relate to three key points:

- the risk of sedimentation of the lake (and especially the reed belt)
- the protection of water quality (chemistry)
- the preservation of good ecological status (biotic communities)

The aim of the synthesis is to provide an assessment that is valid for the entire lake, based on findings at local level, *i.e.,* in the three test areas of Austria and the monitoring points in Hungary. Similarly, the management plan (work package T2) does not aim at measures with a merely local effect but covers the entire lake on Austrian and Hungarian territory.

Table 1. Important goals for water management according to the "Strategy study Lake Neusiedl" (Wolfram et al. 2014).

Fields	Water Management Goals
Hydro-morpho-logy	• Preservation of the hydro-morphological characteristics of the lake basin in the open lake and in the reed beds (landscape element) • Prevention of uncontrolled sedimentation of the reed belt (ratio of open water *versus* reed) • Guarantee of exchange mechanisms between reed and lake water ("water quality")
Reed Belt	• Protection of the uniqueness of the reed belt through conservation and sustainable management (landscape element) • Preservation of the diversity of the reed beds and restriction of reed growth (ratio open water *versus* reed) • Preservation of the reed belt as an integral part of the Lake Neusiedl / Fertő ecosystem ("water quality")
Physico--chemical Parameters	• Preservation of the natural chemistry of the lake as a prerequisite for ecological functioning and good ecological status (salinity, pH, nutrients) • Preservation of the natural spatial and temporal dynamics of the physico-chemical parameters • Low trophic level • Low external and internal nutrient loads
Pollutants	• Maintenance of good chemical and good ecological status (specific and priority pollutants, Annex VIII and X EU WFD)
Biology	• Conservation of good ecological status • Preservation of the natural spatial and temporal variability of biodiversity, abundance, and productivity • Biological processes should run largely undisturbed

1.4 Structure of the synthesis report

In accordance with the tasks described in the previous sections, the synthesis report is divided into the following chapters:

- Chap. 3 Matter transport, processes, and loads
  - Chap. 3.1 Inputs from the catchment area
  - Chap. 3.2 Spatial patterns and gradients
  - Chap. 3.3 Exchange processes
  - Chap. 3.4 Mass balances
  - Chap. 3.5 Long-term trends
- Chap. 4 Scenarios under different conditions
- Chap. 5 Assessment of status quo and alternative scenarios
- Chap. 6 Knowledge deficits and open questions

2 ECOSYSTEM SERVICES

Ecosystem services are defined as the benefits that people obtain from ecosystems (Millenium Ecosystem Assessment (MEA)) (Reid *et al.* 2005), and the direct and indirect contributions of ecosystems to human well-being (TEEB 2010). The resources and services covered by biocenoses and biotopes are fundamental for human well-being and determine the future economic and social development (Figure 3).

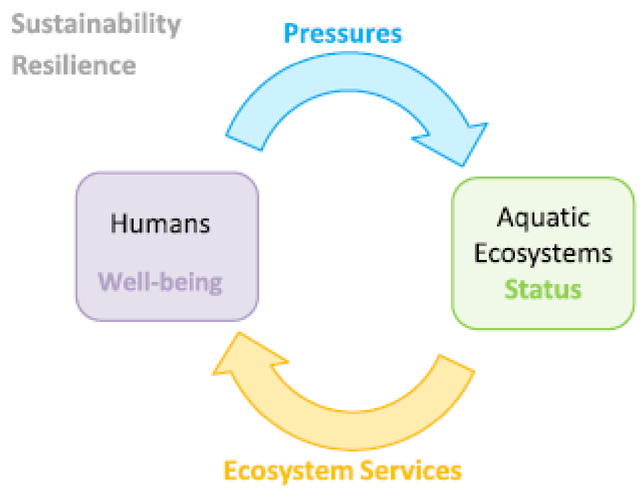


Figure 3. Relationship between humans and ecosystems (from: Grizzetti *et al.* (2016)).

The basic scientific approaches due to the economics and classification of ecosystem services are The Economics of Ecosystem and Biodiversity (TEEB) and Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin 2012). According to the MEA investigations for the common users, the term ecosystem services means benefits which people can get from the nature. These benefits can be valorized or unvalorized in the same ecosystem and be present in different time, space and scale. Main driver for ecosystem services is biodiversity. A rich flora and fauna means a robust natural condition and a lot of service possibilities.

According to MEA, the four water related ecosystem services in case of Lake Neusiedl / Fertő are summarised in Table 2.

Table 2. Water related ecosystem services in case of Lake Neusiedl / Fertő.

Provisioning services	Regulatory services	Cultural services	Supporting services
Fish production	Water quality regulation	Landscape viewing	Nutrient cycling
Fishing	Local climate regulation	Recreation	Primary production
Reed harvesting		Ecotourism	
		Sport fishing	
		Sailing	
		Leisure boating	
		Water sports	
		Venue for open-air theatre	

Scientists of the Hungarian Academy of Science investigated the significance of ecosystems in our everyday life (Báldi *et al.* 2017). High priority was given to Lake Balaton but some of the approaches are valid also for Lake Neusiedl / Fertő.

Implementation of the Water Framework Directive (WFD) has a straight link to ecosystem services. In case of Lake Neusiedl / Fertő, the overall goal of the WFD, *i.e.* achieving or preserving the good ecological and chemical status, as well as the Programs of Measures have to fulfil the ecosystem services needs too (6th World Water Forum 2011). One of the main objectives in this process is to find the way of future sustainable development of non valorized goods for the next generation. The human pressures on the lake are tremendous, in a 100 km radius there are two capital cities with more than 3 million inhabitants altogether (Figure 4).

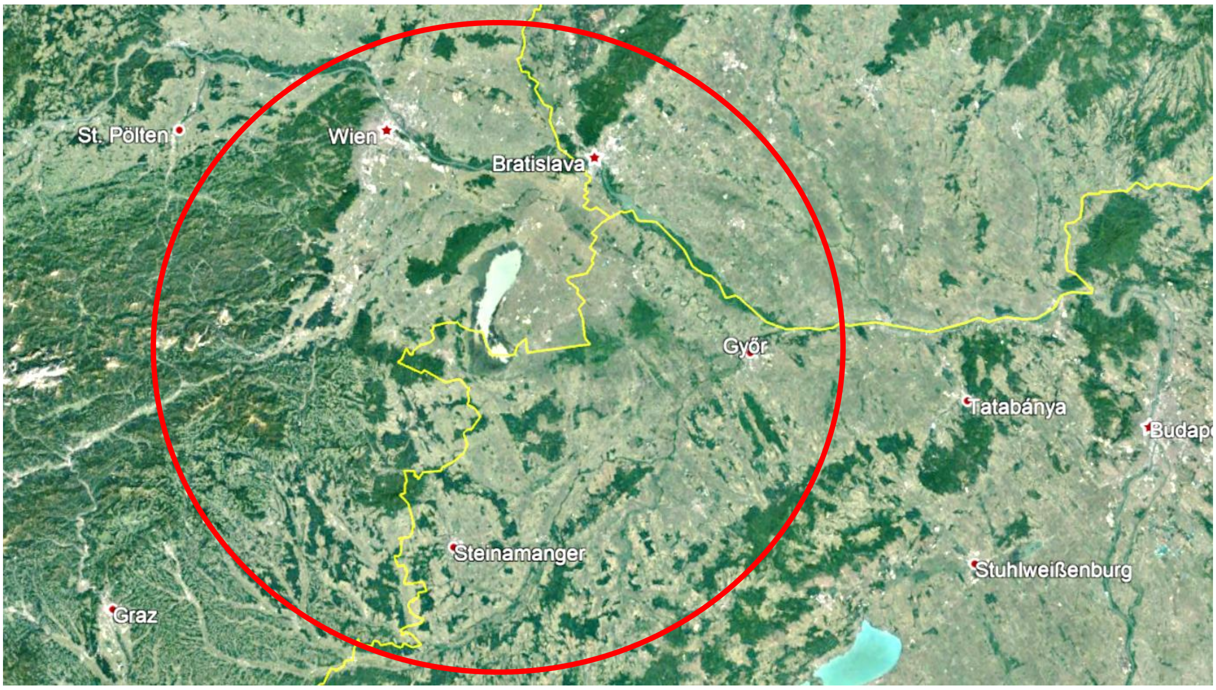


Figure 4. Direct human pressure area on Lake Neusiedl / Fertő. Quelle: Google Earth.

In the catchment area, there is no significant industry. Local people's income is based on tourism, agriculture, and related services; hence the so-called tourism industry is dominant. In 2019, overnight visitors around Lake Neusiedl / Fertő on the Austrian side were more than 1.6 million (Figure 5). Visitors use lake services decisively on the East-shore outskirts of Podersdorf (Statistik Burgenland 2020). On the Hungarian side the numbers are far less but touristic infrastructure in Fertőrákos is under heavy development.

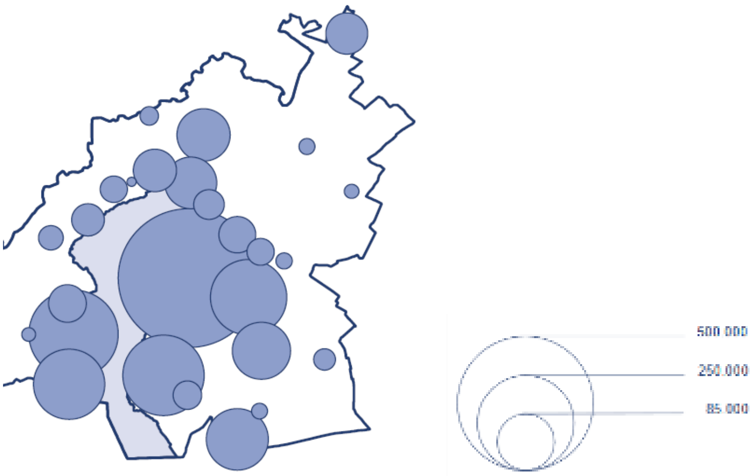


Figure 5. Overnight stays in the region of Lake Neusiedl / Fertő in 2019 (from: Statistik Burgenland (2020)).

Climatic and wind conditions – more than 2,000 sunny hours per year – are favourable for sailing, about 4,150 harbour places exist on the Austrian side of the lake (Kurier 2018). The cross-border national park offers ecotourism, which in the definition of The International Ecotourism Society (TIES 2019) is "responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and involves interpretation and education". TIES lists the following recommendations as principles in this field:

- Build environmental and cultural awareness and respect
- Provide positive experiences for both visitors and hosts
- Provide direct financial benefits for conservation
- Generate financial benefits for both local people and private industry
- Deliver memorable interpretative experiences to visitors that help raise sensitivity to host countries' political, environmental, and social climates
- Design, construct and operate low-impact facilities
- Minimize physical, social, behavioural, and psychological impacts
- Recognize the rights and spiritual beliefs of the Indigenous People in your community and work in partnership with them to create empowerment

The regulatory services and local climatic conditions have a significant impact on the regional wine and vegetables culture around Lake Neusiedl / Fertő. Over the last decades, provisioning services such as reed utilization and commercial fishing have dropped, but the possibilities are still there. Both are connected to other regulatory services like water quality regulation, which was investigated and evaluated in a multidisciplinary approach during the REBEN project.

Special attention must be paid not to overexploit the ecosystem services, because the end-effect will have dramatic consequence for the whole system and may negatively affect also secondary users. Recovery or re-establishment of former ecosystem services are very expensive and do not always meet residents' demands and agreements.

In the near future, there is an urgent need to link the ecosystem services of Lake Neusiedl / Fertő more closely to the environment objectives in order to avoid conflicts between contradictory interests – for the well-being of the people and the ecosystem.

3 MATTER TRANSPORT, PROCESSES, AND LOADS

3.1 Inputs from the catchment area

- *Inputs into the river Wulka*

The Wulka is the major tributary into Lake Neusiedl / Fertő and – in addition to the atmospheric input and the wastewater treatment plants that flow into the lake in various channels through the reed belt (WWTP Jois, Gols, Podersdorf) – it is also the most important input path for external nutrients into the water body. On the one hand, this is due to the intensive agricultural use of the catchment area, from which considerable loads of particle-bound nutrients are washed away into the Wulka. On the other hand, the Northern Burgenland is comparatively low in precipitation compared to other regions of Austria; in dry seasons, the discharge of treated wastewater from the wastewater treatment plants in the catchment area accounts for more than 50% of the low water discharge of the Wulka (Wolfram *et al.* 2019).

While the load of suspended solids in the Wulka originates almost exclusively from agricultural erosion, phosphorus is still emitted in a long-term average of almost 70% via this input path and thus in particulate form into the Wulka. In the case of nitrogen, the majority of the input is in dissolved form, and comes via groundwater and agricultural drainage systems. Agricultural erosion or particulate transport is relatively insignificant. After enhancing of wastewater treatment plant with extensive phosphorus and nitrogen removal, wastewater effluents account to about 20–25% of the emissions into the Wulka for nitrogen and phosphorus.

Trace substances and pollutants are also emitted into the Wulka via diffuse and point sources. Figure 6 shows as an example an estimation of the distribution of the input pathways for the parameters PFOS, PFOA, benzo(a)pyren and fluoranthene for the Wulka itself but also for the whole catchment area of the Wulka including deposition on the lake surface. While the PFOS and PFOA perflourtensides are mainly discharged into the Wulka via wastewater management facilities, PAHs are mainly diffused via erosion (Zessner *et al.* 2019). Atmospheric deposition is also likely to play a major role in the lake itself, although the quantitative data are highly uncertain due to the small number of samples.

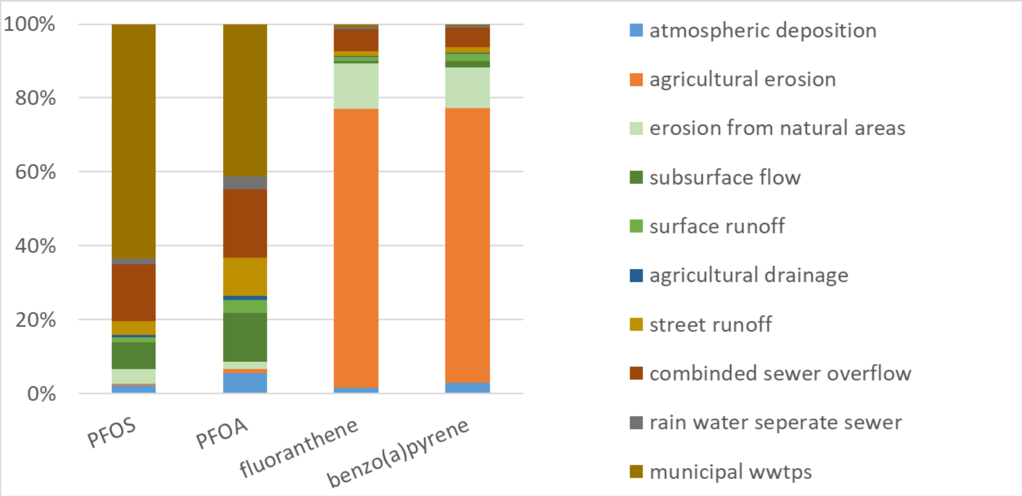


Figure 6. Emission pathways into the river Wulka (Zessner *et al.* 2019).

■ *Inputs from the Wulka into Lake Neusiedl / Fertő*

Before the Wulka actually flows into Lake Neusiedl / Fertő, it flows through the reed belt, where it is several kilometres wide. As has long been known, this is where manifold and complex transformation and degradation processes take place. The fact that the findings from earlier investigations cannot be directly transferred to the present situation is due to the fact that the path of the Wulka through the reed belt has been subject to constant change over the past decades. The exact course of the flow paths was not sufficiently known at the beginning of the project.

As repeated surveys of the area have shown, the once wide flow through the reed belt is no longer as extensive as it used to be. This could be due to the fact that in the course of the regular restoration of the channel sediments were deposited along the reed channels and thus longitudinal dams were created, which only allow a cross-flow only at very few openings of these barriers. However, there are uncertainties in detail, especially concerning the flow paths at higher water levels of the Wulka. In any case, today, at low and medium discharge of the river Wulka the linear flow through man-made channels predominates (Figure 7) (Wolfram *et al.* 2019).

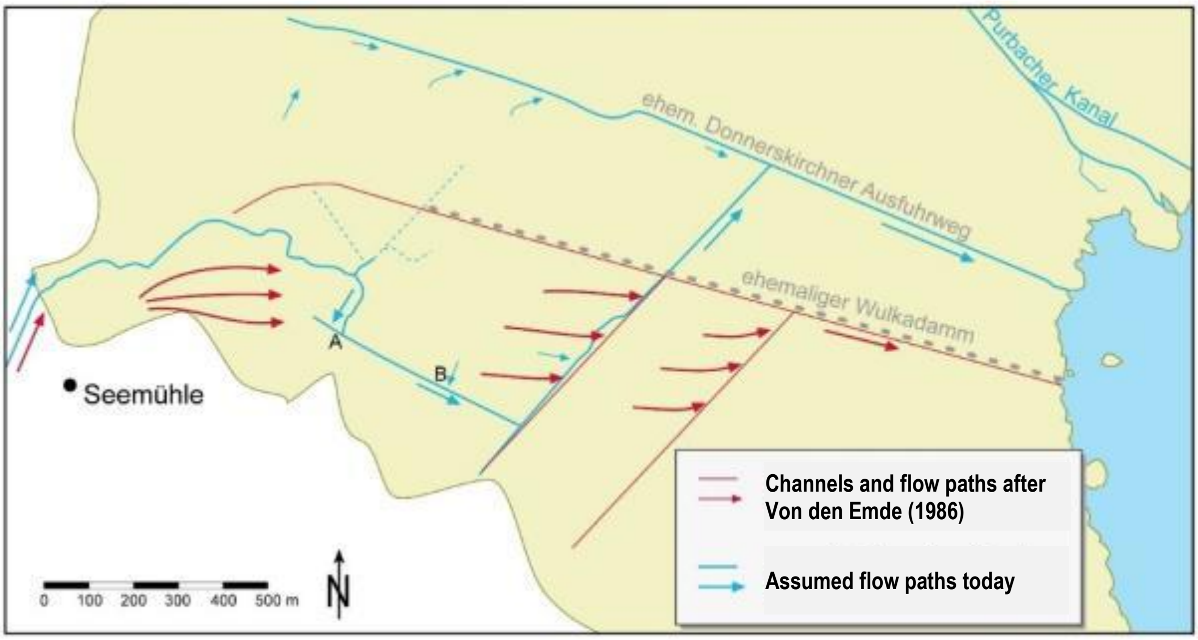


Figure 7. Pathways of the river Wulka through the reed belt of Lake Neusiedl / Fertő in the 1980s (after Von der Emde *et al.* (1986)) and currently assumed pathways.

The current investigations basically confirm the importance of the transformation processes in the reed belt. However, there are clear differences between a faster flow through channels and a diffuse and slow flow through the reed belt with much more pronounced conversion processes (denitrification, retention of solids, dissolution of dissolved phosphorus). Overall, no significant change in total phosphorus concentrations occurred between the Wulka and the mouth into the open lake at the outer edge of the reed belt, as retention of particulate phosphorus and dissolution of dissolved phosphorus were in balance at low to medium discharge. Nitrogen concentrations have been reduced due to denitrification, but there is no evidence of complete depletion of nitrogen up to the mouth of the reed bed in the open lake. At least for the total phosphorus, for nitrogen only partly, the loads transported by the Wulka towards the lake actually seem to reach the open part of the lake at low and mean discharge. This difference to the findings from the early 1980s may be due to the fact that the basic load of the Wulka today is significantly lower than 30-40 years ago (Wolfram *et al.* 2019). (There are less reliable findings for the transport during floods, but the suspended matter measurements at the online water quality stations indicate that a large part of the particulate bound phosphorus remains in the reed belt.)

Nonetheless, two major open questions should not be forgotten. Firstly, it is not certain that the entire Wulka discharge has been sufficiently recorded by the monitoring program of the project REBEN. As emphasized before, the diffuse flow paths of the Wulka are by no means completely known. Secondly, the discharge of the Wulka at the time of the measurements varied between low flow and 2.5 times the mean flow. The conditions and conversion processes during floods could not be recorded within the scope of the project. Therefore, this question should be clarified by means of ongoing tracer experiments at different water levels of the Wulka.

- *Inputs from the Rákos patak into Lake Neusiedl / Fertő*

Within the project REBEN, no specific investigations were carried out on the Rákos-patak, the Golser Kanal or other small tributaries to the lake. They were included, however, in previous matter balances (Wolfram *et al.* 2007; Wolfram & Herzig 2013; Wolfram *et al.* 2012), which allows including the outcome of earlier analyses in this synthesis.

In order to improve the water quality protection of Lake Neusiedl / Fertő, to reduce the external nutrient load of the lake and to reduce the degradation of reeds, two biological wetlands were established, one for the biological post-treatment of the treated wastewater from the Fertőrákos wastewater treatment plant and one for the Rákos stream. Commissioning took place in 2004. Since 2008, the wastewater from Fertőrákos has been diverted to the integrated wastewater treatment plant in Sopron. The Balfi wastewater treatment plant, which previously introduced its treated wastewater into the lake, was closed in 2016. An operational water quality monitoring is carried out at several sites of the Rákos patak wetlands (Figure 1Figure 8).

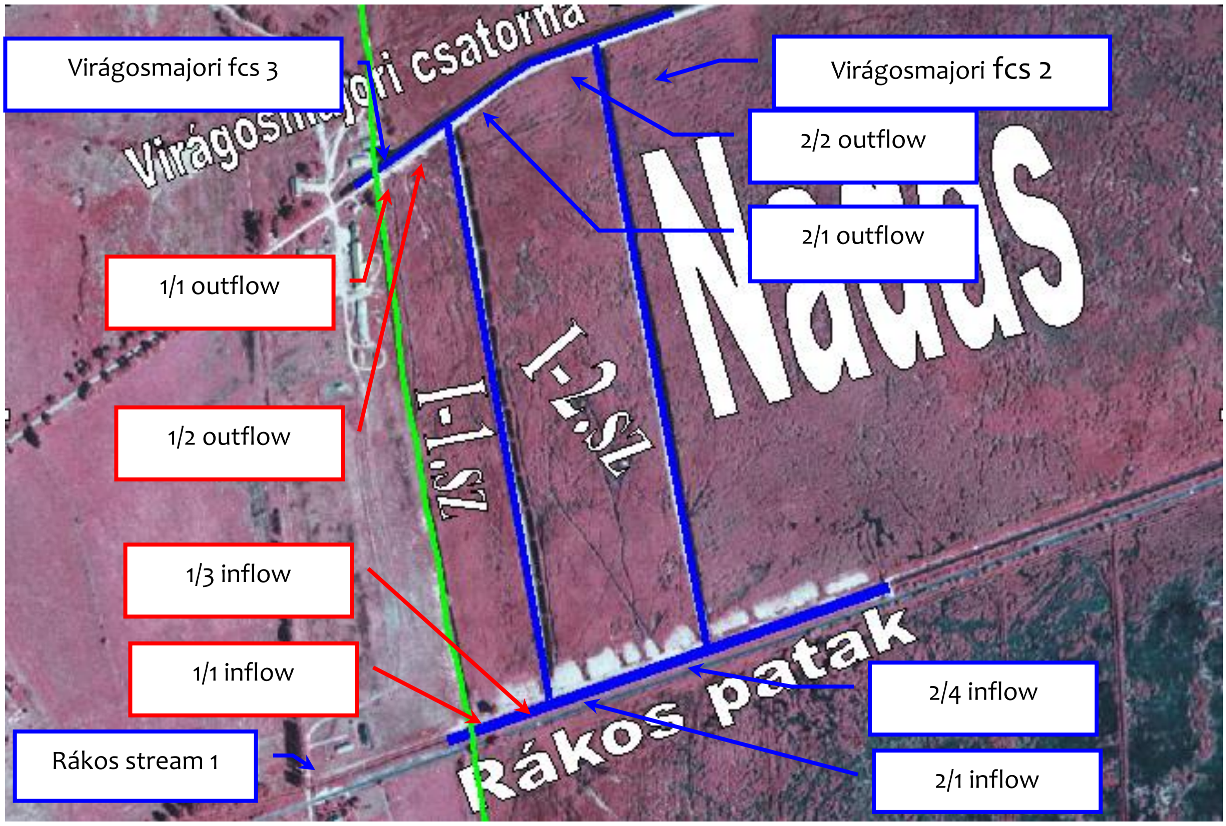


Figure 8. Sampling sites on the wetlands

3.2 Spatial patterns and gradients

■ *Mosaic of reeds and water surfaces*

The reed belt at the mouth of the Wulka is a special case, characterized by a constant influx of material from the Wulka and a directed current from the Wulka towards the lake. The rest of the reed belt is characterized by changing flow directions and mass transport from the lake into the reed belt, but also *vice versa*. But even so, this larger part of the reed belt of Lake Neusiedl / Fertő is not a homogeneous or even monotonous habitat but is characterized by a high structural diversity. On a larger scale, the difference between the several kilometres wide reed belt areas on the western shore or in the Hungarian part and the narrow strip on the eastern shore between Weiden and Illmitz is striking. It results from the higher exposure of the eastern shore to the prevailing NW winds. The stronger mechanical impact of wind and waves on the eastern shore is reflected in the coarser (sandier) sediment and in the different sediment chemistry.

On a smaller scale, the reed belt presents itself as a mosaic of dense reed beds, loose young or old reed and open water areas. The latter form a dense network of narrow channels, but in some areas there are also extensive water areas (pool systems), where the wind finds an attack surface and can locally lead to a stirring up of fine sediments and an autochthonous turbidity in the inner reed belt.

The different structures are not randomly distributed in the reed belt. A broad band of particularly impenetrable reeds runs almost around the entire open lake, while large open water areas are characteristically found in the inner reed belt areas of Mörbisch and Illmitz. From a nature conservation point of view some of these open water areas are often pejoratively called "degraded" as they are probably a late consequence of reed cutting with heavy harvesting machines. Other reed lakes (Herrlakni and Hidegségi in Hungary, Ruster Poschn and Hoadasepplposchnlucka in Austria) are of natural origin.

- *Structural gradients and suspended solids*

Of special interest for the questions of the project REBEN are hydro-morphological and material gradients between the reed edge to the open lake and the landward border of the reed belt. One obvious gradient concerns the water depth, which decreases from the lake-reed-border towards the pre-lake meadows, whereas the actual transition to land is difficult to grasp due to the water level fluctuations. Nevertheless, this transition area is likely to play a significant role for the nutrient turnover in the reed belt since it is subject to complex conversion processes due to the frequent change from wet to dry conditions.

However, the water depths in the reed belt on the lakeward side are by no means uniform and clearly defined. The so-called "lake dam" is a linear sediment agglomeration along the reed-lake edge, which results from turbidity of water drifting into the reed belt and subsequent deposition of fine sediment in adjacent reed areas of low turbulence. Unfortunately, multi-temporal data on the height of the dam in different parts of the reed belt are not sufficient to gain a consistent information on its spatio-temporal changes. The analyses of E. Csaplovics (Report 2 of the Austrian expert team) show at least the range of dynamics of height variations based on the extended surveys of the late 1980s and the significantly limited amount of respective data from the GeNeSee project. (Figure 9).

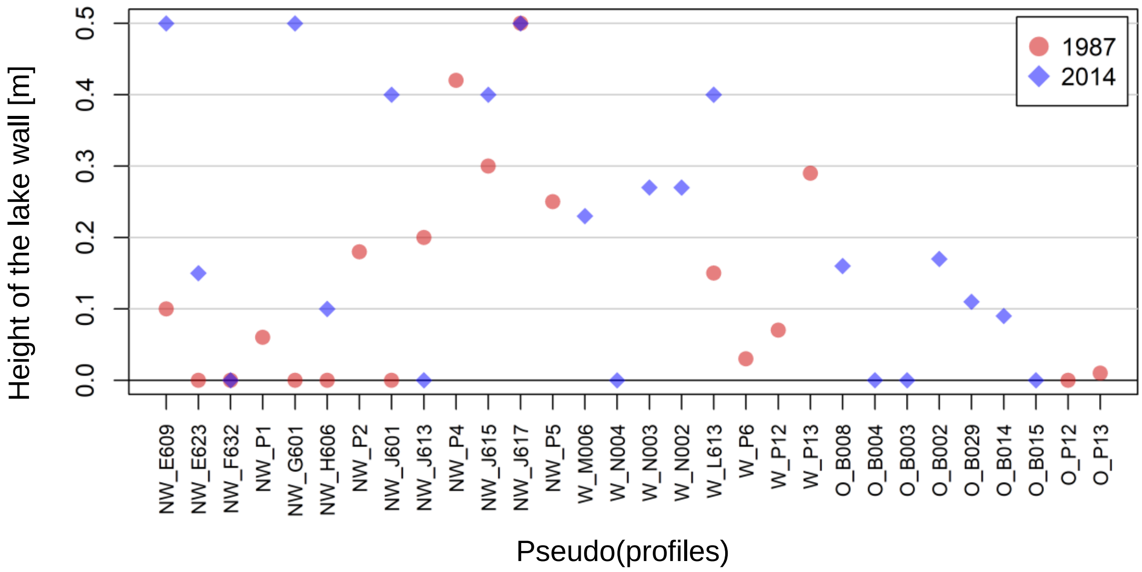


Figure 9. Height of the lake dam at several profiles and pseudo-profiles at the lake reed boundary (from chap. 3 in Report 2 "Reed structure and morphology" of the Austrian expert team).

The numerous artificial channels are gaps in the lake dam and at the same time the preferred transport paths from the lake to the inner reed belt areas. Along these linear structures, decreasing gradients of suspended matter, *i.e.,* inorganic particles as well as plant and animal plankton, are observed. However, the channels are also migration routes for fish, which in spring seek suitable spawning grounds or, depending on the environmental conditions, more favourable locations in the reed belt or in the open lake.

■ *Dissolved matter*

The results of the project REBEN underline the importance of the channels for different chemism within the reed belt of Lake Neusiedl / Fertő. In areas that are poorly connected or not connected to the open lake, the concentrations of dissolved water constituents can be three times higher than in the open lake. Values of electrical conductivity up to >6 000 µS cm^{-1}, chloride concentrations of 800 mg L^{-1} and alkalinities up to almost 40 mMol L^{-1} were measured. The concentration leads to shifts in the relative proportions of the ions due to precipitation of calcium.

Isolated and poorly connected water areas in the inner reed belt are also characterized by temperature extremes (>35 °C) and large diurnal temperature fluctuations. A consequence of the reduced exchange with the open lake are intensified degradation processes in small-scale structured reed beds, which result in intensive oxygen consumption up to completely anoxic conditions in summer and autumn.

In terms of nutrients, the campaigns of the present project documented a decrease in silicon (depletion by reeds, Characeae and planktonic algae) and nitrate (denitrification) as well as an increase in dissolved organic nitrogen and organic carbon (concentration, accumulation of humic substances) and total dissolved phosphorus (concentration and re-dissolution) along the transects from the lake to land.

Also for some pollutants the significant difference between the concentrations in the inner reed belt and in the open lake indicates a concentration or re-dissolution process, which complies with the findings from the laboratory experiments (higher mobilization rates at higher temperature and low oxygen concentration).

■ *Sediment*

The physico-chemical composition of the sediment resembles the gradients of the respective parameters in the water. For example, the organic content and water content along the transects from lake to land increase significantly. At isolated sites loss of ignition of up to >40% and a water content of up to >95% were measured in the very loose, flaky sediment. It can be assumed that a high percentage of humic complexes in the organic material prevents the sediment from compacting. Various pollutants are positively correlated with the organic content (*e.g.,* PFOS). As far as nutrients are concerned, an increase in the total phosphorus content per g of dry matter was demonstrated in the course of the project REBEN, while the content per area (and thus per sediment volume) decreases towards the land. Among the different forms of phosphorus binding, it is mainly the organic fraction and the fraction bound to humic substances that increases landward along the transects.

In summary, the following factors and causes for the gradients found in the project REBEN could be confirmed:

- the water level (depending on precipitation and inflows *versus* evaporation and discharges)
- human uses (reed cutting) – especially in its long-term effects through damage to the reed and the development of extensive water areas in the inner reed belt
- the construction and restoration of channels, which act as priority transport routes between the open lake and the inner reed belt

It is not new that these hydro-morphological factors and conditions are of major importance for the water quality of the lake. With the project REBEN, however, the interrelationships between the various factors and parameters could be determined and described much more precisely and the distribution patterns and temporal variability documented in detail. Of special importance, however, is the step from the qualitative description to a quantification of exchange processes (Chapter 2.3), which is the basis for the estimation of loads (Chapter 2.4).

■ *Ecological gradients*

Within the reed belt, plankton communities and the fish population are characterized by clear but opposite gradients from the open lake towards the land. It should be noted that especially the plankton in the reed belt does not form only slightly modified "lake communities" but presents itself as an independent species assemblage.

The differences in the populations of phytoplankton, zooplankton, and fish at the isolated sites in the reed belt underline the importance of the connection to the open lake. The extreme physico-chemical conditions in the mostly wind-protected and calm areas of the reed belt allow the emergence of a specialized and diverse planktonic biocoenosis, which in the absence of significant fish densities (and thus predators) can develop diversely and with high densities and biomasses. With poor connections to the open lake and thus limited migration possibilities for fish, the comparatively good food supply in the inner reed belt can therefore only be used to a limited extent by fish, since the majority of these are restricted to areas close to the lake and well connected.

From a fish ecology point of view, improved connectivity between the open lake and the water areas in the inner reed belt would therefore be desirable. The attenuation of physico-chemical extremes would enable an increased "colonization" of these areas by fish and open up new spawning grounds and food resources for them. For phyto- and zooplankton, however, increased connectivity would result in an increased exchange between the two large sub-habitats, which would have a positive effect on biodiversity.

3.3 Exchange processes

■ *Factor time*

The hydrological and material gradients within the reed belt – shown in the previous chapter and in detail in the Reports No. 3 to No. 5 of the Austrian expert team – are by no means static, but only typical, to a certain extent "average" distribution patterns and results of complex exchange processes but are ultimately subject to considerable temporal variability.

The mass transfer takes place on different levels:

- between the open lake and the reed belt

- between different areas within the reed belt
- between sediment and water column

and in different temporal rhythms. Due to its size and shallow water depth as well as its geographical location in the Pannonian lowlands, which are characterized by strong winds, Lake Neusiedl / Fertő is subject to two main hydrological rhythms:

- the periodicity of the meteorological water balance (*i.e.*, the seasonally fluctuating relationship between precipitation and evaporation), and
- the change between windless phases and those with strong influence of wind and waves

These two external factors – precipitation/evaporation and wind – are the decisive meteorological-hydrological timers for the exchange processes in the lake. They are superimposed by the daily rhythm of light (as a timer for photosynthesis and thus for the rhythm of oxygen production and decomposition processes) and the annual and daily rhythm of the water temperature (Figure 10).

Of particular interest for the exchange processes are the wind setup/setdown and the accompanying *seiche* movements (standing waves) of the lake. The NW winds prevailing at the lake are often subject to a daily rhythm, which leads to a tilting of the water surface in north-south direction. The surface displacements are weaker in the east-west direction and seiche oscillations have a short period, between 30 to 60 minutes.

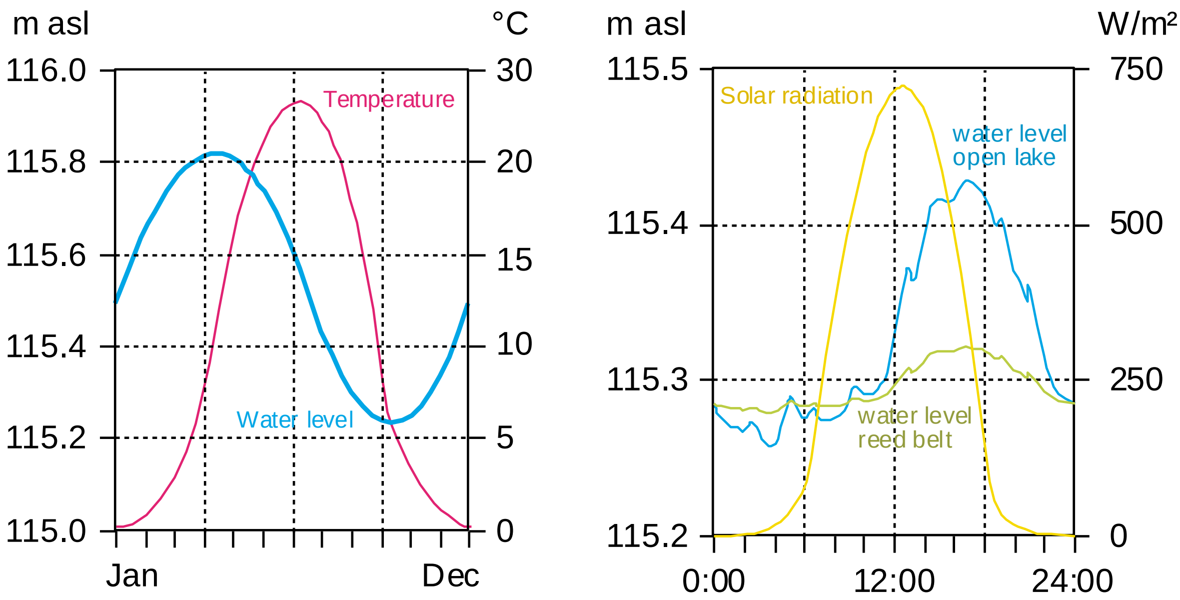


Figure 10. Scheme of main rhythms at Lake Neusiedl / Fertő. Left: seasonal with water level and temperature, right: diurnal with typical wind event and corresponding surface displacement, and global radiation.

- *Sediment – water (laboratory tests)*

The exchange processes in the sediment-water transition zone are extremely complex and difficult to quantify with on-site measurements. In order to be able to describe the most important relationships and influencing variables, laboratory tests on the adsorption and mobilization of selected substances were therefore carried out in the project REBEN.

The adsorption tests showed that for certain substances, *e.g.*, PFOS, the sediment still has a sufficiently high adsorption capacity, *i.e.*, the sediment in the reed belt can still act as a sink for these pollutants. For other pollutants, *e.g.*, some heavy metals, the adsorption capacity is almost exhausted, *i.e.*, the ability to adsorb further substances is currently low. This means that there is also a fundamental potential for a re-solution or concentration increase in the future. That this has not happened (yet) is probably due to the fact that new sediment (especially Ca-Mg-carbonates) is generated constantly and provides new adsorption surfaces. Turbidity is therefore not only of great importance for the decomposition of organic material (see Krachler *et al.* (2009)), but also for adsorption and thus as a sink for pollutants.

In the different experimental approaches with variable water temperatures and oxygen concentrations (but also varying pH values), no recognizable influence of these variables on adsorption was proven, but they did have an influence on the mobilization of pollutants. At least some heavy metals were mobilized at higher temperatures and under anaerobic conditions (or lower pH values). For the pollutants PFOS and PFOA a significant mobilization potential could be demonstrated even under aerobic conditions. This also applies, with limitations, to phosphorus, whose mobilization rates were most clearly influenced by the initial concentration.

The different reactions to changed oxygen and temperature conditions in different experimental settings (overflow *versus* shaking tests) allow the conclusion that the conditions at the sediment surface are of great importance for the mass transfer at the sediment-water transition zone. This finding is relevant for considerations of sediment turbulence, be it wind-induced in open water areas in the reed belt or man-made in the course of channel restoration. With regard to the different structures in the reed belt, it could be deduced that in open reed bed systems like in the inner reed belt of Mörbisch there is a greater – and ultimately more effective or quantitatively more significant – potential for the remobilization of pollutants and nutrients than in narrow, dense reed areas with low wind attack and reduced flow. On the other hand, there is a higher risk of anaerobic conditions in dense reed stands, which also leads to an increased remobilization of pollutants such as some heavy metals, PFOS/PFOA and probably also phosphorus.

■ *Open lake – reed belt (water quality monitoring stations and wind event)*

The water and mass exchange between the open lake and the reed belt was documented in detail within the framework of the project REBEN using the water quality monitoring stations, the series of measurements in autumn 2019 (wind event) and the hydraulic modelling. At low water levels, the exchange takes place almost exclusively via channels. A diffuse flow through the reed, as described for the lake in the 1980s, is only possible when the water level clearly exceeds the top of the lake dam at the outer edge of the reed belt to the lake. Even then, however, the numerical modelling in the Illmitz area showed that the diffuse inflow of lake water depends very much on the respective reed structure. Model calculations with a wave up to 115.80 m asl (above Adriatic Sea level) and a still existing "permeability" (expressed by the Manning-Strickler coefficient of $k_{St}=4\ m^{1/3}\ s^{-1}$) of the inundated reed area showed that a diffuse inflow of lake water can indeed occur far into the reed belt. Similar observations were made in the reed belt in the area of the Wulka. However, there are also indications that a reed stand is hardly permeable and acts more like a "weir", with practically no diffuse flow. In this case two phenomena can be observed:

i. The reed areas are slowly wetted or filled up from the larger water areas connected to the lake in the landward part of the reed belt, and/or
ii. there is a flow through the multitude of existing small and smallest channels, which in turn are fed from the larger open water areas connected to the lake.

From the monitoring campaigns during the project phase, estimates of possible exchange rates could be obtained from measurements over two to three days with high temporal resolution in one channel each in Illmitz (see Figure 11) and Mörbisch as well as from the data from the online stations. The measurement campaign in Illmitz also enabled the verification of the numerical modelling (see Report 1 "Hydrology" of the Austrian expert team).

In the channels, surprisingly high **flow velocities** of up to several decimetres per second are achieved in case of strong winds and corresponding water surface displacements. With an assumed channel cross-sectional area of 2 m² (5 m width × 0.4 m depth), this corresponds to a flow rate of up to 1 m³/s. Over a longer period of time, large masses of water are thus transported from the open lake into the reed belt and back again via a single channel. Figure 11 shows an example of the course of the water level at three monitoring stations near Illmitz. In the rearmost areas of the reed belt an increase of >10 cm was measured over several days. With a water surface of >14 ha in the open brown water areas near site IL5 (see Report 3 "Chemistry" of the Austrian expert team) this corresponds to a water transport of >14.000m³!

The **duration of the inflow and outflow phases** can easily be read from video recordings and from the data recordings. The events can last for several days (see Figure 11), but can also be very short (*e.g.*, a few minutes). The latter can be seen in the recordings of the water level in an unsteady, jagged course, *i.e.*, flow phases with (relatively) high flow velocity and rest phases, in which the flow direction is reversed, alternate at short intervals. For mass transfer, this means an alternation of transport (partly erosion) and sedimentation.

The extent of the exchange via the reed channels depends on the water level on the one hand and on the size and shape of the reed channels on the other. In narrow places (*e.g.*, in the region Illmitz height, outer edge to the open lake between monitoring site IL3 and the so-called Zander Bay, see Report 3 of the Austrian expert team) the sediment is extremely hard, which suggests a permanent erosion of the fine sediments and very high flow rates (jet effect). In the inner reed belt, however, bottlenecks can also impede the flow and cause a braking effect, which facilitates the penetration of the reed and leads to an increasing "clogging" of the channel. The process of **silting up of the reed channels** then accelerates until the water exchange stops completely. The result of such a development – a channel that silts up and is overgrown by reed after a few meters – can be seen for example in the former fishing channels between Ruster Poschn and the open lake, at measuring site IL8 (see the Austrian Report 3) as well as in the fishing channels in the conservation zone of the national park in the southern part of Lake Neusiedl / Fertő (*e.g.*, the so-called Thell Channel), which have not been maintained for a long time. This development can be rapid and takes only a few years. The hydraulic models impressively show that the water exchange between the open lake and the reed belt can decrease by one to two orders of magnitude as a result of sedimentation of the reed channels. This effect could also be shown very clearly in the numerical model (see Report 1 "Hydrology" of the Austrian expert team).

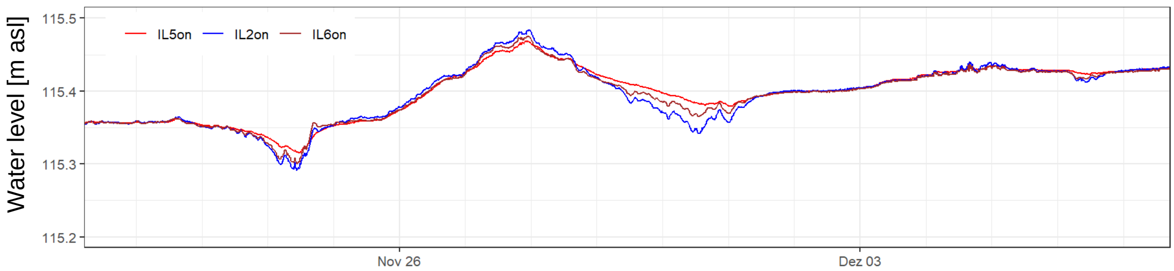


Figure 11. Course of the water level at three monitoring stations in the reed belt of Illmitz between 22 Nov and 7 Dec 2018. Station IL5on lies in a large, open brown-water area with >14 ha; a rise of water level of 10 cm corresponds to a water inflow of >14 000 m³.

The situation described above with a water transport of more than 14 000 m³ over two to three days was demonstrated in an area with **large open water areas in the inner reed belt.**

Such areas are found for instance near Illmitz and Mörbisch. For the Mörbisch area, maximum daily loads in one channel were estimated to be up to 40 000 m^3, which corresponds to the daily inflow of the river Wulka at low discharge.

Without open water areas in the inner reed belt (*e.g.*, in dense reed beds at Oggau or Breitenbrunn) the potential for water transport is inevitably lower, since only the channel system itself and a close-meshed mosaic of small pools can absorb the water from the open lake. It can be assumed that the limited water transport and thus the reduced input of suspended matter into the reed belt will enhance sedimentation of sediment in the open lake, *i.e.*, in bays and in the protected lee behind reed islands. Observations of strong sediment deposits at the southern edge of the large reed island in the national park seem to support this hypothesis.

In addition to the reed structure in the inner reed belt, the **location and shape of the reed channels** are important for the exchange of water and matter. The continuous water quality data from the area Mörbisch showed that the largest input of suspended matter into the reed belt is given when the wind blows exactly into the channel and thus literally "pushes" the turbid lake water into the reed belt. Most of the channels at Lake Neusiedl / Fertő are located on the western shore and are laid out in a W-E direction; the described effect is therefore only given with a (relatively rare) east wind. Channels on the eastern shore of the lake (from Illmitz to Apetlon) have or would have a greater potential for water and mass transfer between the open lake and the reed belt. Presumably, the shape (straight *versus* "angled" and with bottlenecks) and the cross-linking of the channels also influence the water and matter input into the reed belt. This is indicated by the hydrological investigations in the Hungarian part of the reed belt, which is characterized by a dense network of channels.

Namely, wind can induce considerable horizontal mixing in **the extensive Hungarian part of the reed belt** by gravitational forcing along the perimeter, rather than directly via wind shear. As described in Report 1 of the Hungarian researchers, it has been demonstrated by numerical modelling that the flushing distance is about 1 km in cases when the wind surge overtops the lake dam by 1 to 2 decimetres. Airborne laser scanning survey in the GeNeSee project was not able to resolve the submerged microtopography of the reed bed, including the bathymetry of long-abandoned canals and brown-water ponds, so shallow flooding can only be modelled with a reduced accuracy.

Even in the newly dredged Hungarian channels, bed roughness and more importantly the submerged lateral reed together exert a considerable hydraulic resistance on the flow. Calibration resulted in a low Strickler coefficient of 10 $m^{1/3}/s$ which is typical of vegetated channels and is not much smoother than the roughness of the reed bed assumed in the Austrian modelling.

Wind surges in the open lake penetrate into the canals as shallow translatory waves, *i.e.*, the surface waveform and water mass move in the same direction. These boundary-driven **surface waves attenuate with distance** according to their frequency. Seiche oscillations (with a period of 1 hour or less) quickly decrease to a fraction of their boundary amplitude within a few kilometres, confirming conclusions of earlier studies (Takáts 1984). In contrast, the aperiodic component of surges, wind setup or setdown that has a time scale of days penetrates into the reed canals as kinematic waves, with little loss of amplitude.

As to wind waves, their effect is constrained up to a distance of 10 to 30 metres into emergent vegetation (Irish et al. 2008), which nevertheless has a significant impact on reed stands.

Since the prevailing wind direction is NW-NNW, wind surge is often higher in Madárvárta/Vogelwarte Bay than in Fertőrákos Bay, creating a water surface gradient between canal mouths. In the southern reed zone, this drives a **mean annual net flow** of 5 to 15 litres/second (per canal) between these two bays in the circumferential canals against the prevailing wind direction, that is, from SE towards NW (Figure 12). This flow rate corresponds to a mean current velocity in the order of 0.001 m/s which can flush brown-water from the circumferential canals into Fertőrákos Bay in about 50–100 days (counting with a mean canal cross section of 7 m^2 at low lake water level).

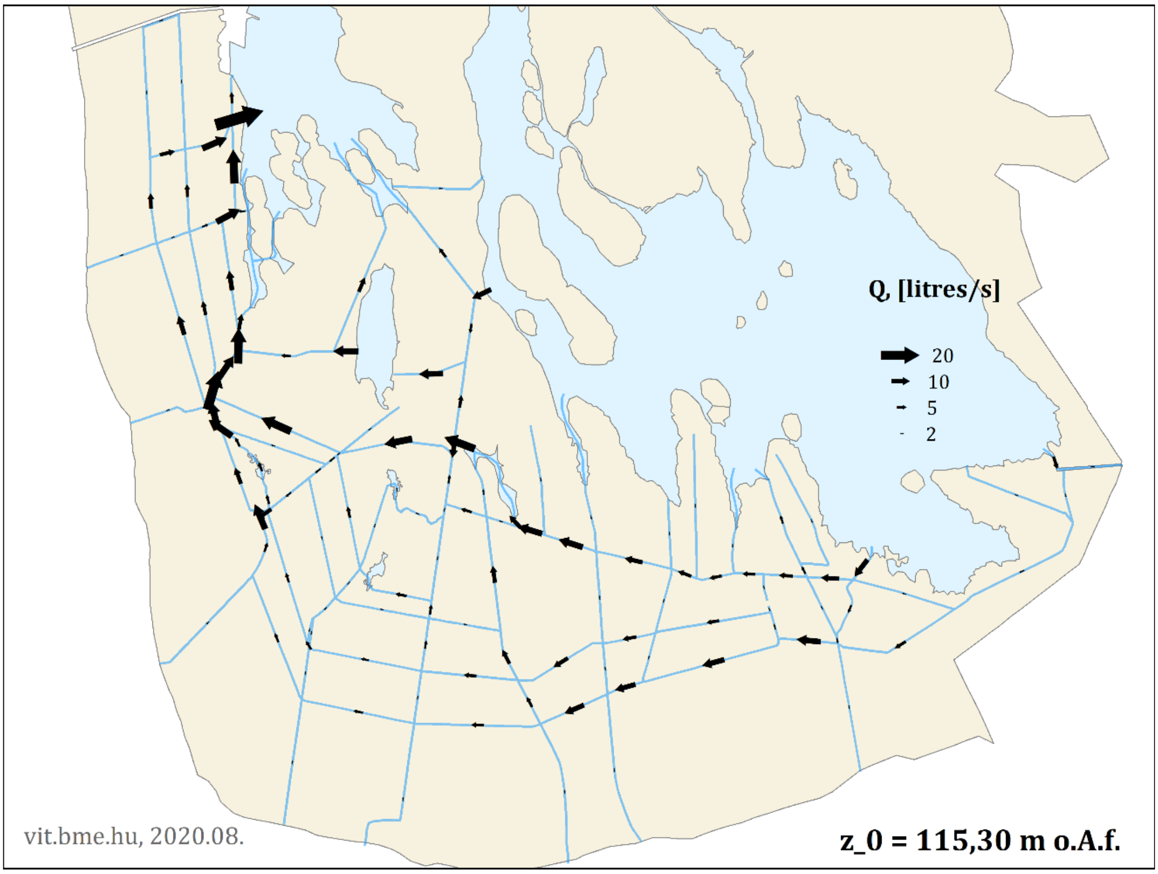


Figure 12. Map of the net annual average flow in the Hungarian reed belt, simulated for low lake water level (115.30 m asl).

Residual water displacements will result in some advective mixing between the open lake and the reed belt, both during wind setup and setdown. The zone swept by lake water is about 1.2 km wide in the southern reed belt, which is true for low to high mean lake water levels. This penetration distance is also demonstrated in the turbidity of ponds in the sweep zone, whereas ponds further away are transparent (Padisák 1993). When a strong wind surge occurs during low to medium water level (*i.e.*, with unsubmerged reed bed), a significant amount of the lake water is retained in terrain depressions at the end of the storm.

In **summary**, it can be said that at present the channels in combination with the open water areas behind them are of the greatest importance for the water and mass exchange between the open lake and the reed belt. The channels are the preferred transport routes for suspended matter (as well as particle-related nutrients and pollutants) into the reed belt as well as for dissolved matter (*e.g.*, dissolved phosphorus) from the reed belt back into the open lake. Only at high water level, a diffuse flow through the reed belt can occur. However, even then it is of little relevance as compared to transport through the channels. However, as the progressive raising of the lake dam at the outer edge of the reed belt towards the lake shows, the contact between lake water and the reed belt is of high importance in this edge area of the reed belt.

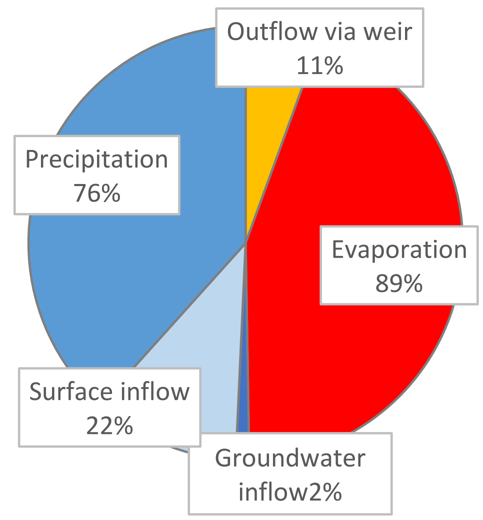
Although the silting-up of the lake over the past 20 to 30 years could not be proven by survey data from the project GeNeSee, it is a very likely scenario and leads in the long run to an increasing separation of the two main compartments of Lake Neusiedl / Fertő.

3.4 Loads of sediment, nutrients, and pollutants

3.4.1 Water balance

Total water balances for Lake Neusiedl / Fertő have been made for a long time, beginning with the systematic records of the Hydrographic Service. In the present project, however, the focus is on the exchange between the open lake water area and the reed belt of Lake Neusiedl / Fertő. Therefore, existing balances are presented for an overview. In the following, possible changes in the balance due to the expected changes in climate are discussed.

Although the question of the size of the evaporation is always a very difficult task in a balance (often as a remaining part of the balance), the evaluations show the great importance for Lake Neusiedl / Fertő. Only in very rainy years the evaporation is lower than the annual precipitation. This circumstance is also an essential factor for the future development (Figure 13, Table 3).



Water balance 1965–2018, mean values in mm/a	
Precipitation	579
Surface & groundwater inflow	180
Sum +	759
Evaporation	667
Outflow through Hanság channel	84
Sum –	751

Figure 13. Water balance of Lake Neusiedl / Fertő 1965–2018 (Amt Bgld. Landesregierung, Abt. 5).

Table 3. Water balance of Lake Neusiedl / Fertő catchment area, derived from data in the period 2000–2012 (Source: Wolfram *et al.* (2014)).

Component	Area [km²]	without groundwater discharge		With assumed groundwater discharge	
		Annual rate [mm/a]	Volume [10^6 m³/a]	Annual rate [mm/a]	Volume [10^6 m³/a]
Precipitation	1116	596	665	596	665
Total positive	**1116**	**596**	**665**	**596**	**665**
Evaporation catchment (without lake)	796	466	371	466	371
Evaporation lake (reed and water area)	320	866	277	796	255
Evapotranspiration reed	182	878#	160	756#	138
Evaporation open lake	138	850	117	850	117
Groundwater outflow		0*	0	20*	21
Superficial outflow	1116	16	18	16	18
Total negative	**1116**	**596**	**665**	**596**	**665**

* Assumption, # Residual value

Likewise, the runoff via the Hanság Channel plays an important role in the water balance. The now valid weir operation regulations accordingly control the lake water level, provided that there is enough water for a control. The effect of this control since the 1960s on the lake water level is illustrated in Figure 14, which shows a significant rise of the lake level and less variations.

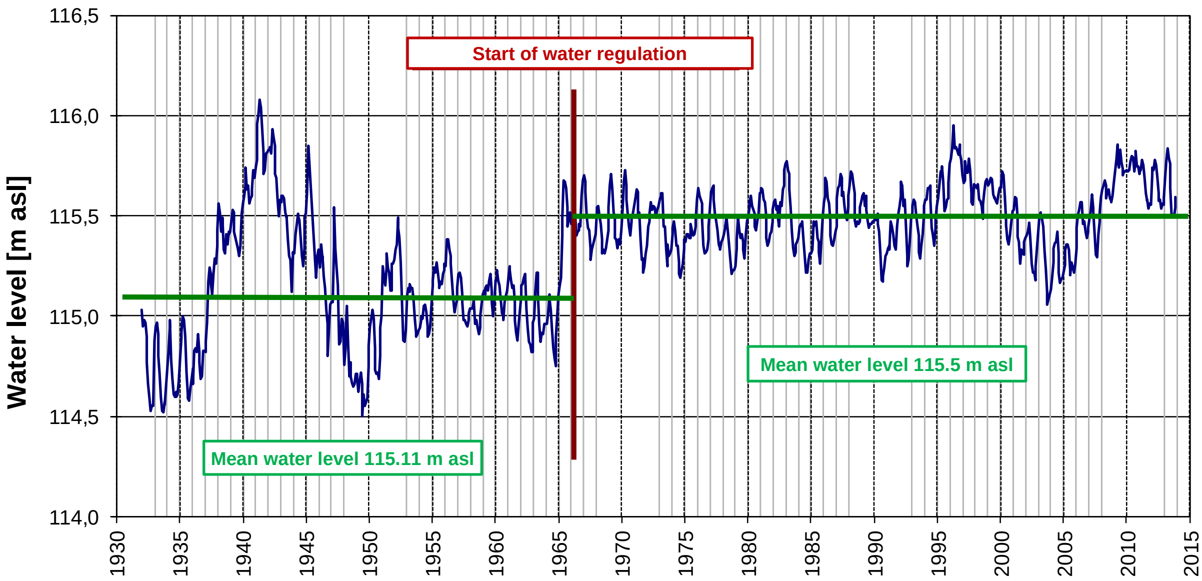


Figure 14. Hydrograph of the lake water levels 1932–2013. Source: Amt der Bgld. Landesregierung, Referat Hydrographie.

As investigations in studies on climate change have shown (Blöschl *et al.* 2018; Blöschl *et al.* 2011; Schöner *et al.* 2011), an increase in air temperature is to be expected, which in any case will also lead to increased evaporation. Furthermore, the climate models on which the studies are based show that there will be a slight increase in precipitation in eastern Austria. Although this statement is to be regarded with greater uncertainty as compared to the increase in air temperature, it remains open to what extent there will be an effect with regard to the water balance. The results of seasonality assessment (Report 1 of the Hungarian researchers) indicate drier conditions (*i.e.*, less precipitation and/or inflow) for January, June, November, and December, while May, September, and October seem to become wetter. The monthly mean temperature trend analysis showed the strongest increase for July and August. There is one thing the investigations clearly show: The area of Lake Neusiedl / Fertő and its surroundings is highly sensitive and vulnerable as regards water management issues.

Quotation from Schöner *et al.* (2011):

Lake Neusiedl / Fertő

- *Since the water balance is the difference between two approximately equal numbers (precipitation and evaporation), forecasts of the lake's water balance are very uncertain (strong evidence).*
- *The scenario with the CLM climate model (2021–2050 compared to 1976–2007) results in an increase of air temperature by about 1 °C and an increase of precipitation by about 5%. Under these conditions, the lake level remains approximately the same as it is today (weak evidence).*

The uncertainty in long-term predictions is also confirmed by the finding by Hungarian researchers (Report 1) that climate change will likely lead to decreasing amounts of water discharged from the lake via the Hanság Channel. The results for the worst-case scenario predicted a –198 mm annual deficit to a 24 mm gain in the water balance, projecting decreasing lake water levels in the future. Falling water levels will increase the drainage of the soil adjacent to the channels and will ultimately dry the habitat. Unless winds become stronger in the future, wind surges that cause extensive flooding in the southern belt will be much rarer.

3.4.2 Suspended solids

The data shown below serve as rough estimates of the loads, in- and outflows between catchment area and lake as well as between the open lake and the reed belt. The data basis and the time reference of the loads estimated are very heterogeneous. Therefore, the calculations cannot be combined to a conclusive balance. The figures are intended to provide orders of magnitude to assess the importance of the individual loads.

In this synthesis, we provide only a short description of the balance items. For an in-depth description of the database and the rationale of the individual figures we refer to the synthesis of the Austrian investigations (Wolfram *et al.* 2020).

The listed quantities of sediment and suspended solids that enter the lake, are formed in the lake or transported within the lake are summarized in Table 4. As mentioned above, these figures do not allow for a true mass balance, mainly due to uncertainties in assumptions and the high temporal variability. Despite all uncertainties, the following statements can be derived from this compilation:

1. The solids from the Wulka remain for the most part in the reed belt of the mouth. This also applies to very large, flood-induced loads, which can exceed the annual load of a year with little runoff on a single day.
2. The newly formed sediment (Ca-Mg-carbonates, lime mud or "Kalkschlamm") in the lake exceeds by far the solids entering the lake from the catchment area.
3. In years with large amounts of lake water discharged via the Hanság channel, a considerable load of turbidity and thus fine sediment is also abstracted from the lake.
4. The regular dredging in the marinas and bathing areas is not only a local measure to prevent silting up but has a noticeable influence on the overall sediment balance of the lake.
5. Nevertheless, larger suspended matter loads are continuously transported from the open lake into the reed belt and are therefore a driving factor of potential siltation in these areas.
6. Just like the regular dredging of the marinas and bathing areas, the channel maintenance works have a noticeable influence on the overall sediment balance of the lake. The dredging of sediment from the channels permanently removes solids from the lake, even if they remain within the boundaries of the lake basin. Lateral deposits in the form of longitudinal dams have a lasting effect on the structure and character of the reed belt.

The numbers in Table 4 are shown as a flow chart for visualization in Figure 15. It must again be noted here that the estimates do not result in a truly balanced balance sheet. This was not to be expected in view of the numerous assumptions, fuzziness, and uncertainties. The "balance items" are rather intended to give an impression of the magnitude. In particular, it should be taken into account that some balance items were determined for the whole lake (*e.g.,* lime mud or "Kalkschlamm"), others only for Austria (*e.g.,* dredging). Autochthonous organic production was also not included. Another uncertainty exists in the case of the transport (erosion, deposition) within the open lake, *e.g.,* in bays like the Rust Bay or in the structured southern part of the Lake Neusiedl / Fertő. The general situation, however, can be described.

Table 4. Estimation of sediment loads (t/a) from the catchment area to the lake, internal loads, and output. Positive loads (import to the respective compartment) are highlighted in yellow, negative loads (export from the respective compartment) in blue.

input/output/transport	total	Reed belt Wulka	Open lake	Other Reed belt
input				
Wulka [1)]	3 890 (740 – 24 230)	3 773 (718 – 23 500)	117 (22 – 730)	0
other paths of input				
other feeders	440	0	13	427
WTP	52	0	2	50
dry deposition [2)]	3 000	95	1 315	1 595
new formation				
inorganic ($CaCO_3$)	10 000 (7 500 – 14 500)	0	10 000 (7 500 – 14 500)	0
organic	n.a.	n.a.	n.a.	n.a.
output				
discharge via Hanság channel	1 600 (0 – 11 450)	0	1 600 (0 – 11 450)	0
ports/bays dredged	6 800 (50 – 16 600)	0	6 800 (50 – 16 600)	0
channel restoration [3)]	3 140 (450 – 9 070)	160 (20 – 450)	0	2 980 (0 – 8 620)
Internal loads				
transport open lake -> reed belt	0	0	9 666 (9 250 – 10 082)	9 666 (9 250 – 10 082)

1) ca. 3% transport into the open lake
2) Splitting to 140 km² open lake and 180 km² reed belt, thereof 10 km² in the area of the Wulka mouth
3) evaluated as discharge, since permanently excluded from future exchange processes
n.a. = not assessed

An earlier estimation of sediment transport is available from Stalzer & Spatzierer (1987). The authors estimated the lake-internal, wind-induced transport of suspended matter from the open lake into the reed belt at about 13 000 t/a. Despite all methodological differences, this value corresponds well with the value determined in the project REBEN (ca. 9 700 t/a).

The estimated loads are mostly in the range of 4 to 5 powers of ten of tons per year. Compared to the total sediment volume of the lake of over 200 million m³ (Csaplovics *et al.* (1997) or the equivalent of about 100 million tons (dry matter), this is negligible. The fact that especially the uppermost layer of the lake sediments is in closer and more frequent exchange with the open water, however, puts the figures and annual loads into a different light and underlines the potential importance of the sediment balance for long-term changes of the lake in morphological (sedimentation), qualitative (water quality) and ecological terms (ecological status).

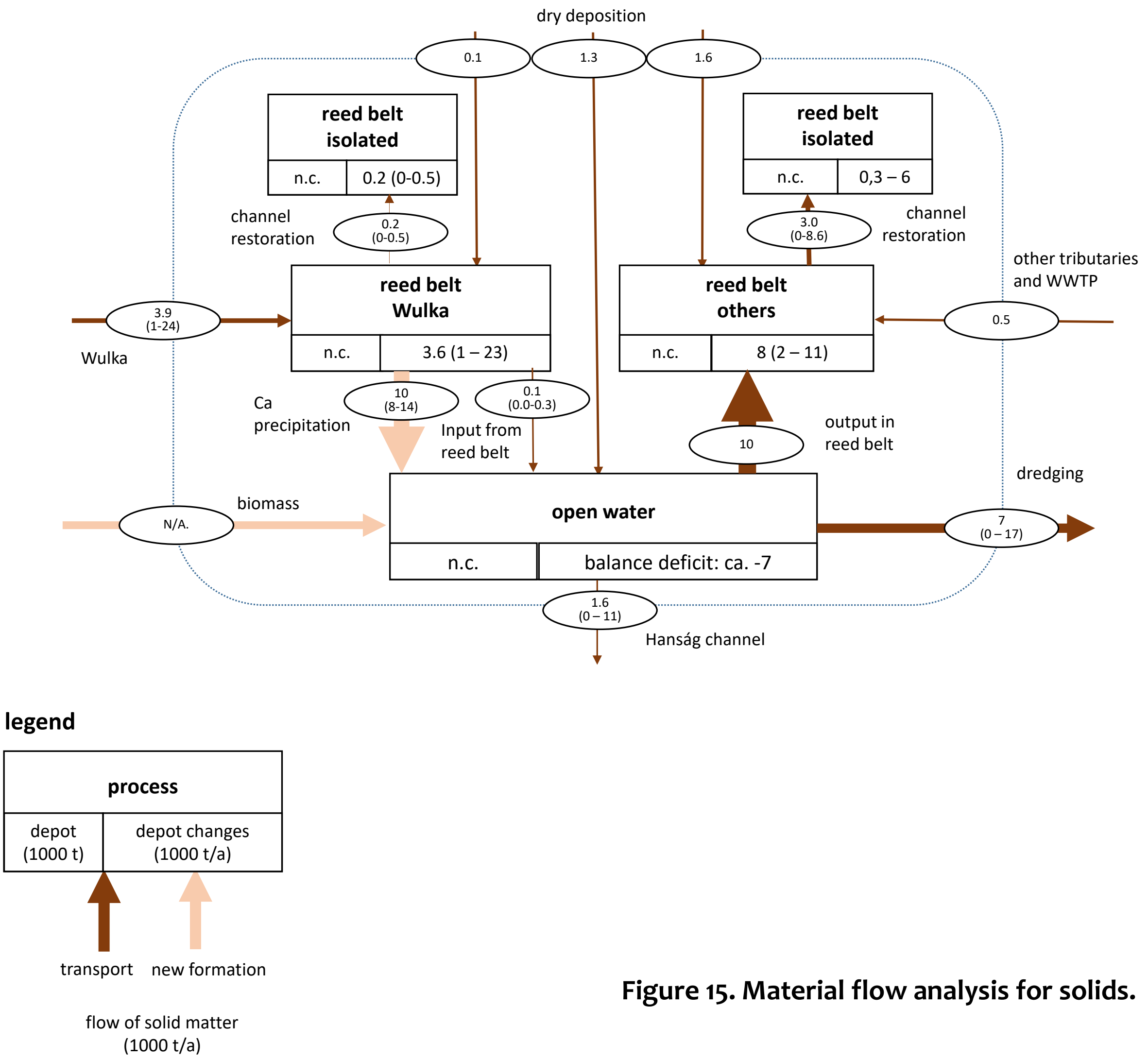


Figure 15. Material flow analysis for solids.

3.4.3 Nutrients (phosphorus)

The following considerations on the nutrient balance of Lake Neusiedl / Fertő are based essentially on earlier studies, from the first detailed research in the 1980s (Brossmann *et al.* 1984) to the long-term calculations of the 2010s (Wolfram *et al.* 2007; Wolfram & Herzig 2013; Wolfram *et al.* 2012). The calculations of Wolfram *et al.* (2012) showed the importance of sedimentation and the connection of the reed belt to the open lake. However, the type of nutrient deposition was unclear in detail, but also the location. Here, the investigations of the project REBEN can contribute important new findings (Table 5, Figure 16):

1. In contrast to the solids, nutrients (phosphorus) are retained in the Wulka mouth to a minor degree and largely reach the open lake at low to medium discharge – even if

partly delayed. Only secondarily, phosphorus from the open lake is transported back into the reed belt.

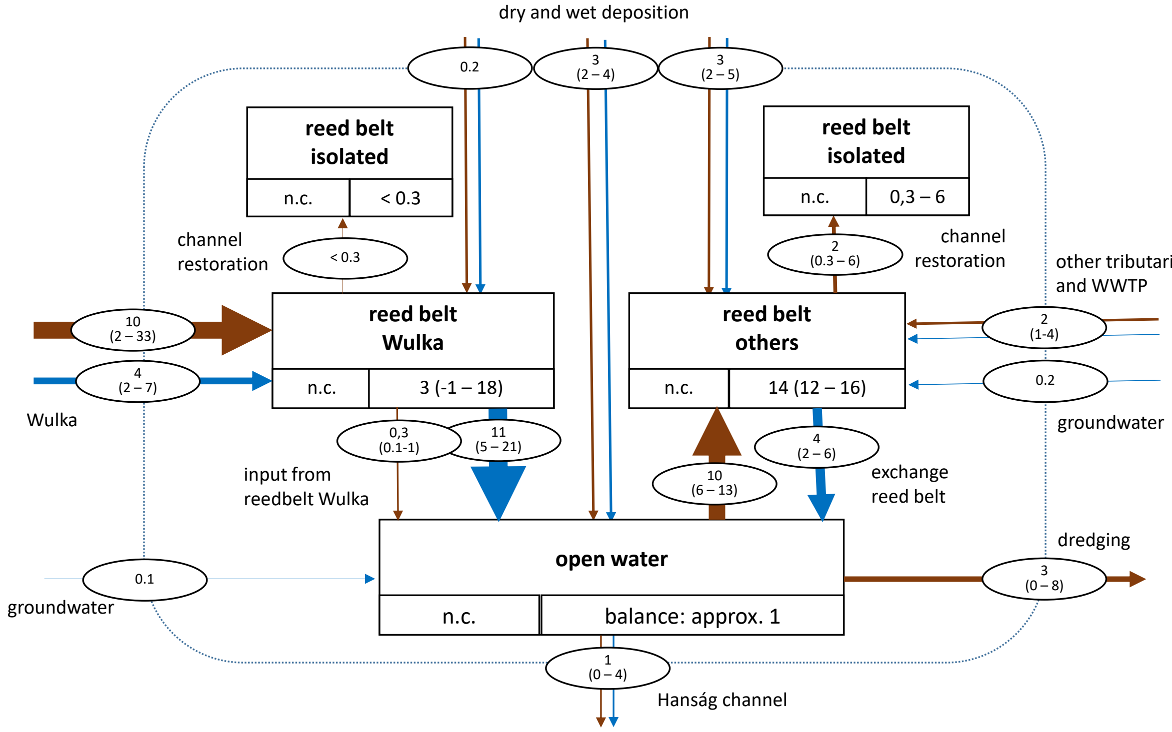
2. On a long-term average and over a longer period of time about 3 t of phosphorus from the Wulka catchment area remain in the reed belt and do not reach the open lake. The Wulka reed belt is therefore an important retention area for nutrients. In dry years without strong flood events, however, the reed belt at the Wulka mouth does not act as a sink but as a source of phosphorus. This does not mean an increased load for the open lake, but only reflects the low input from the Wulka catchment area in years with low discharge.
3. Among the external inputs, the Wulka accounts for only slightly more than half of the total inputs in contrast to earlier (1980s) years with a higher portion (see Herzig & Wolfram 2013). While in the solid matter the autochthonous production of lime mud (calcite, “Kalkschlamm”) contributes significantly to the total amount of solid matter in the lake, there is no comparable balance item for phosphorus.
4. Both in the area of the Wulka and in the other reed beds there is a significant release of dissolved phosphorus into the open lake, which is lower than the input of particulate phosphorus into the reed belt.
5. Dredging is not as important for the nutrient balance as it is for the sediment mass balance, but it does contribute to a significant removal of nutrients from the system and is, apart from the discharge via the Hanság Channel, the only possible export from the lake basin.

As with solids, the annual input and output and the intra-lake transport of phosphorus are negligible compared to the total amount of nutrients present in the lake. However, phosphorus is mainly bound to sediment, *i.e.*, sedimentation (in the reed belt) is equivalent to permanent removal from the system. As already known from previous studies (*e.g.*, Gunatilaka (1986)), the sediment can be a nutrient source – both at the mouth of the river Wulka and in the reed belt – but the net discharge from the open lake into the reed belt predominates.

Table 5. Estimation of phosphorus loads (t/a) from the catchment area to the lake, internal loads and output. Positive loads (import to the respective compartment) are highlighted in yellow, negative loads (export from the respective compartment) in blue.

Input/output/transport	total	Reed belt Wulka	open lake	Other reed belt
input				
Wulka incl. HW (1992–2009)	14 (4 – 40)	3 (-1 – 18)	11 (5 – 22)	0
particulate	10 (2 – 33)	9,7 (1,9 – 32)	0,3 (0,1 – 1)	0
dissolved	4 (2 – 7)	6,7 (2,9 – 14)	10,7 (4,9 – 21)	0
other input pathways (part. + diss.) *)	10 (6 – 16)	<1	6 (3 – 10)	4 (2 – 5)
other feeders	2 (1 – 4)	0	2 (1 – 4)	0
WTP (ab 2001)	0,2	0	0,2	0
dry deposition	3 (2 – 4)	0,1	1,3	1,6
wet deposition	3 (2 – 5)	0,1	1,5	1,8
groundwater	0,3 (0,2 – 0,5)	<0,1	0,1	0,2
output				
discharge via Hanság channel	1 (0 – 4)	0	1 (0 – 4)	0
ports/bays dredged	3 (0 – 8)	0	3 (0 – 8)	0
channels restoration	0,3 – 6	max. 0,3	0	0,3 – 6
reed harvest	n.a.	n.a.		n.a.
internal loads				
open lake -> reed belt				
i. estimation from mass balance *)	0	0	18 (7 – 35)	18 (7 – 35)
ii. estimation from loads	0	0	9,5 (6–13)	9,5 (6–13)
particulate	0	0	10,5 (7–14)	10,5 (7–14)
dissolved	0	0	1	1

*) Numbers from the sediment mass balance of Wolfram *et al.* (2012), which included the whole lake, but with rough estimates only for the Hungarian part (*e.g.* Rákos-patak). In the 1980s, Pannonhalmi (1984) estimated the total deposition (wet, dry) in the Hungarian part of the lake with 1 t/a.
n.a. = not assessed



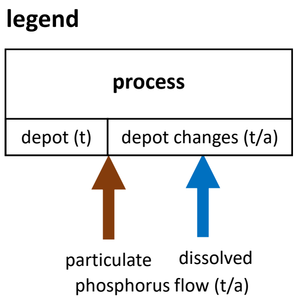


Figure 16. Material flow analysis for phosphorus.

3.4.4 Pollutants

■ *Concentration gradients*

The first objective of the investigations for pollutants was to obtain information on the occurrence and fate of substances from different areas of origin and with different areas of application and different environmental behaviour. Accordingly, the investigation parameters were selected. However, monitoring compliance with the environmental quality standards (EQS) of the Austrian Ordinance on the Quality Objectives for Chemicals in Surface Waters (Qualitätszielverordnung Chemie Oberflächengewässer) or examining all substances regulated there was not the task of these investigations. Nevertheless, the examined parameters show that, in addition to the known problems with mercury and PBDE in biota, the contamination with PFOS, fluoranthene, benzo(a)pyrene and other PAHs with high molecular weight must be considered critical with regard to a possible failure to meet the EQS. Additionally, for lead in the open lake, indications of exceedance of EQS have been found. However, an unambiguous verification of exceedances in the water phase would have to be carried out by means of a suitable monitoring program with 12 samples per year and sufficiently accurate analysis.

For the selected chemicals in this study a first assessment on their environmental behaviour in the lake and its reed belt can be performed already based on their concentrations in the influent via Wulka as well as in the open lake and in the reed belt. Parameter names in parentheses show conflicting results and a high uncertainty in respect to this assignment.

The investigated substances that show a clear degradation or conversion under the environmental conditions of the lake; pharmaceuticals: carbamazepine, diclofenac und bezafibrate; complexing agents: EDTA, NTA und benzotriazole; pesticide metabolites: chloridazon-desphenyle; (poly- and perfluorinated chemicals: PFOS), (sweetener: acesulfame K).

Substances that are persistent in the lake to a high extent, which leads to an enrichment in the water phase; pesticide metabolites: N,N-dimethylsulfamid; poly- and perfluorinated chemicals: PFOA, PFPeS, PFHpA, (PFNA und PFHxA); (sweetener: acesulfame K).

Substances that are retained in the reed belt mainly from the Wulka estuary via sedimentation of suspended solids to a significant extent; PAHs with higher molecular weight: *e.g.,* benzo(a)pyrene, fluoranthene; metals: *e.g.,* copper, lead, nickel, zinc.

Substances which show adsorption to the sediments in the reed belt, that leads to a reduction of dissolved concentrations in the lake as compared to Wulka or in the reed belt as compared to the lake; (poly- and perfluorinated chemicals: PFOS); (metals: cadmium, copper, lead, nickel, zinc).

Substances which show tendencies for mobilization out of the sediments of reed belt at field investigations, which could lead to legacy pollution from the reed belt to the lake; (PAHs: benzo(a)pyrene, fluoranthene;).

This selection includes those substances for which indications of a possible exceeding of the EQS were found (PFOS, fluoranthene, benzo(a)pyrene and lead (dissolved)). In addition, the substances chloride, PFOA and EDTA are presented to show typical patterns of environmental behaviour in comparison. For the evaluation and presentation chosen here, in addition to the investigations carried out in the project REBEN and summarized in Chap. 5 of Report No. 3 “Physico-chemical parameters and pollutants” (Austrian expert team), data from previous investigations, especially in the Wulka, were used. The use of external data allows a more comprehensive presentation. Used sources are explained in more detail in Zessner *et al.* (2019).

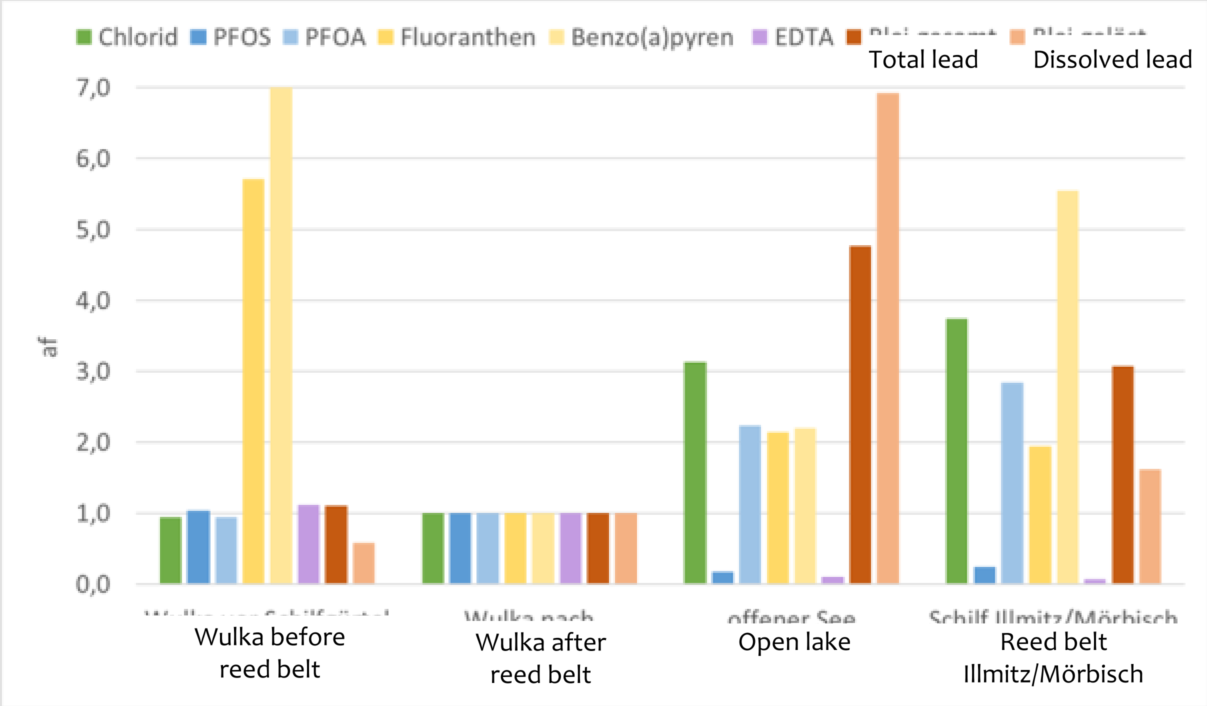


Figure 17. Enrichment or decrease factor (af = C_n/C_0) for selected substances. C_n means concentrations in each water phase and C_0 was chosen the concentrations in the inflow from the Wulka reed belt to the open lake.

On the Hungarian part of the lake, through the growing season of 2019, the open lake and the reed channels were mostly in "good", and in some cases "high" status according to the classification of the Water Framework Directive (Report 2 of the Hungarian researchers). High gradients were found, namely "poor" water quality status within reed stands were adjacent to reed channels in "good" status. None of the measured and averaged concentrations of inorganic (heavy metals, PAH, PCB and TPH) and organic micropollutants exceeded the environmental limits in the Hungarian decree, except benzo(a)pyrene.

Loads

For PFOS, PFOA and fluoranthene, essential material flows into and out of Lake Neusiedl / Fertő will be compared by means of material balances. In contrast to solids and phosphorus, the system under consideration was simplified due to the lower level of information on the pollutants. Inputs and outputs are considered for the lake reed belt system as a whole. Changes in the system's storage indicate retention in the reed-belt reservoir, whereas the representations of the pollutants do not distinguish between the reed belt in the area of the mouth of the Wulka and the other reed belts.

The compilation does not claim to be quantitatively accurate, but it should allow a comparison of orders of magnitude and an identification of balance sheet gaps. For this reason, no uncertainty margins are given here. The figures given are only to be understood as indications of the order of magnitude of the respective material flow. The estimation uses the water balance components for inflow and outflow to the lake and links these with PFOS, PFOA and fluoranthene concentrations in the Wulka before the reed belt, after the reed belt and in the open water of the lake. The output out of the system is calculated with the mean outflow via the Hanság channel and concentrations in the open lake. (In the time of investigation of REBEN the weir was closed.) In addition, estimates of atmospheric deposition from Zessner *et al.* (2019) are used to consider this input path in the balance. As Figure 16 (left) shows, in PFOS the inflow is supplemented by a depositional input of the same order of magnitude. The discharge of PFOS via the outflow in the Hanság channel is very small compared to the inflow due to the low concentrations in the lake. For example, a discharge of about half a kilogram of PFOS per year contrasts with a discharge via the outflow of only 0.01 kg per year.

Altogether, the known material flows cannot explain the excess of PFOS input over discharge. PFOS is considered extremely persistent in the environment (Beach *et al.* 2006). Under certain conditions, however, the elimination of PFOS seems possible. However, this may lead to the formation of predominantly short-chain PFT, whose persistence is much higher than that of PFOS (Trojanowicz *et al.* 2018). Results of the adsorption tests show that PFOS can potentially be further eliminated from the aqueous phase of the lake by adsorption, which could be a relevant pathway from the open lake into the reed belt sediments (Report 6 “Laboratory Tests” of the Austrian researchers).

Overall, the PFOS balance of Lake Neusiedl / Fertő thus indicates that PFOS is largely eliminated from the lake water. A complete mineralization seems less likely. More probable seems to be a conversion to short-chain PFT as metabolites, whose further fate in the environment is unknown. Furthermore, an adsorption of PFOS to the reed sediment can also provide a removal from the lake water.

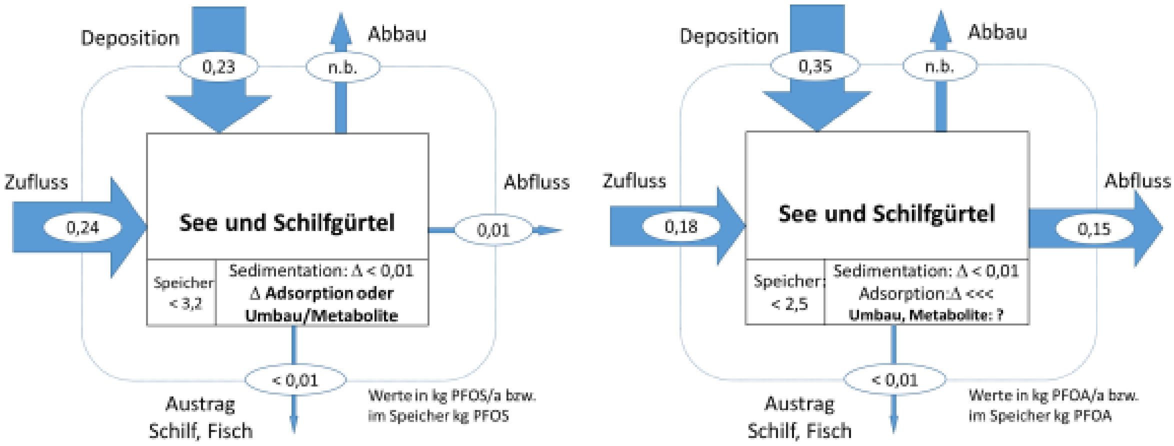


Figure 18. Estimation of a substance balance of the lake Neusiedl / Fertő (long term water balance combined with substance concentrations from 2017–2019) for PFOS (left) and PFOA (right)

The situation for PFOA is similar to PFOS (Figure 18, right). The input via deposition is likely to exceed that via surface tributaries, and the estimated discharge cannot fully explain the fate of the inputs into the lake. Differently, the elimination of PFOA is much less extensive than for PFOS, a lake concentration remains significantly higher than in the Wulka, and thus the discharge via the Hanság channel is of a similar order of magnitude as the inflow (mainly via the Wulka). A relevant adsorption of PFOA on the reed sediments can be excluded on the basis of the results from the Austrian Report 6 "Laboratory Tests". Thus, at least the substance load, which is discharged into the lake via deposition, can not to be found in the known outputs out of the lake and the balance indicates relevant degradation or transformation processes in the lake, where short-chain PFT as metabolites cannot be excluded as the final product.

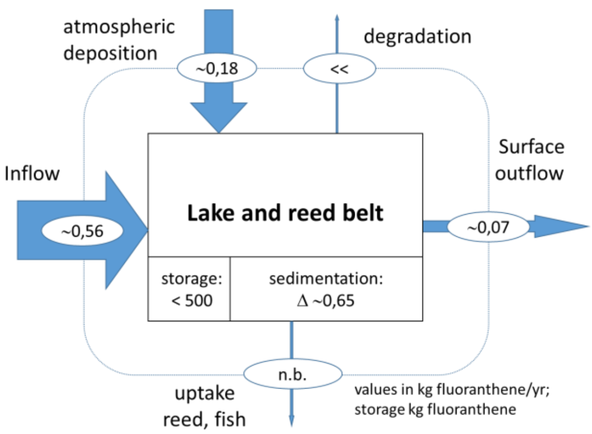


Figure 19. Estimation of a substance balance of the Lake Neusiedl / Fertő for fluoranthene (long term water balance combined with substance concentrations from 2017–2019).

At first glance, the balance for fluoranthene (Figure 19) also resembles that for PFOS. An input via inflow and deposition is opposed by a significantly lower discharge via outflow. Thus, the lake also serves as an effective sink for fluoranthene. Closer inspection reveals a clear difference. For example, the fluoranthene reservoir in the lake sediment is about 2 orders of magnitude larger than that for PFOS. For fluoranthene, removal from the open lake water via sedimentation can already be clearly demonstrated in the reed belt of the Wulka. Also for the rest of the reed belt there is clear evidence for a removal of fluoranthene via sedimentation of suspended matter. This situation also indicates a potential for release from the reservoir in the reed belt, as could also be shown for phosphorus. However, the extent to which this back load actually occurs cannot yet be estimated from the available information.

3.5 Soda lake characteristics

Lake Neusiedl / Fertő is known as the largest soda and the westernmost steppe lake in Europe, and the diverse water bodies of Lake Neusiedl / Fertő present a unique ecosystem with all the characteristic sodic habitats of the Carpathian Basin, which are determined by multiple extreme physical and chemical environments and biogeochemical processes. The cosmopolitan reed (Phragmites australis) has been playing a major role in this ecosystem. Its population dynamics and local characteristics are significantly influenced by the extreme environmental factors and biological succession of reed bed also has a great impact on its environment.

The shallowness and fluctuating water level of the lake resulted in an arid steppe climate. Consequently, in the closed inner ponds and reed zone the daily temperature variation can reach even 10–20°C range, and it is expected to increase by climate change in the future.

3.5.1 Chemical water composition

Among the Hungarian soda types of inland waters (wetlands and lakes), the most common is the basic soda ($NaHCO_3$) type such as the Lake Neusiedl / Fertő, but with regard to anions, the soda-chloride and soda-sulphate subtypes also occur in the astatic pans of Seewinkel (Fertőzug) area.

The salinity varies between 1.5 and 2.5 g L^{-1} in semi-static Lake Neusiedl / Fertő. The typical soda lakes and pans are characterized by a permanent alkaline environment (pH: 8–10), related to the alkalinity. The other important physical and chemical properties as the high turbidity is caused by high inorganic suspended solid concentration (Secchi-disc transparency 1–20 cm), which is characteristic in the open water of the Lake Neusiedl /

Fertő, and the high (polyhumic >16 mgC L^{-1}) dissolved organic carbon content (DOC) with hypertrophic nutrient state. These environmental drivers represent a multiply extreme conditions, special nutrient (C, N, P) cycles, trophic system, and ecosystem.

The high DOC content of water is mainly the product of the internal (autochthonous) decomposition of reeds. The significant part of dissolved organic carbon is coloured dissolved organic matter (CDOM), which gives the characteristic brown colour of the water in the reed stands, and the permanently alkaline environment plays a major role in maintaining the high concentration of humic substances.

The oxidation reduction potential – hereinafter referred to as redox potential – in the sediment has also a significant impact on the cycling of materials, determining plant growth directly by the available amount of nitrogen, phosphorus and partly carbon in the sediment.

Lowest total (TOC) and dissolved organic carbon (DOC) concentration values were found in the open water of Lake Neusiedl / Fertő ("ATHU2 Vogelwarte -Madárvárta 2 project), whereas highest values in the inner, scarce reed stands, thus carbon accumulating in declining reed stands results in a polyhumic state (extraordinarily rich in humic substances). However, a closer cognition of the phenomenon needs further focused research. Significant correlation between TOC and total nitrogen (TN) implies that TN content is determined by organically bound nitrogen, therefore highest TN values could be detected in declining reed stands. However, the quantity of mineral nitrogen accessible for algae (ammonia and nitrate nitrogen) were in all habitats by two orders of magnitude lower than the total nitrogen content, arising from the accumulation of slowly decomposing organic (humic) matter deriving from reed. Annual mean soluble orthophosphate phosphorus accessible for algae was on average by one order of magnitude lower than the quantity of total phosphorous being a very low value, by several orders of magnitude lower than values of thousands typical for the periodic soda pans of the Seewinkel. However, the ratio of total nitrogen and phosphorous is relatively high (average of 46), especially as compared to the periodic soda pans where this value stays often below 1. As for trophic proportions, according to the annual average of total phosphorous concentration (OECD) all studied habitats, water bodies were classified as eutrophic, whereas according to the annual average of chlorophyll-a concentration only as mesotrophic, being also a characteristic of soda pans in the Carpathian Basin (Boros *et al.* 2017).

3.5.2 Biological quality elements

The species composition of the phytobenthos stocks moderately deviates from that of the community characteristic of the type, and it is much more intensively disturbed than in the case of a good status. The population density moderately deviates from that of the communities which are characteristic of the type. On certain sections, the phytobenthic stock may be damaged by bacterial colonies and coats outgrowing as a result of anthropogenic effects.

The fresh weight of phytoplankton biomass ranged between 100 and 5,000 μg L^{-1} while species composition showed significant differences in the seasonal and habitat variation. The main characteristic of the spring phytoplankton is the pico-cyanobacteria dominance in the open water (Somogyi *et al.* 2010), while these algae are absent in the reed belt and inner ponds. Besides the real planktonic algae the other characteristic group of the open water is the meroplankton (Padisák & Dokulil 1994), they are absent in the reed belt, but their contribution to the total phytoplankton is very variable depending on the wind mixing of the water column. Therefore, the picoplankton and meroplanktonic organisms are the best indicators of the relationship between different habitats of the reed belt and the open water. There is one characteristic salt indicator species, *Chaetoceros muellerii*, which occurred in low abundance in the whole lake. There are distinct diverse communities of algae in the reed stand, where beside the planktonic algal species numerous periphytic/benthic species occurred. The phytoplankton communities of the open water and died reed bed significantly differ from the reed zone. The habitats in the reed zone with the inner ponds constitute a more or less homogenous group (Figure 20).

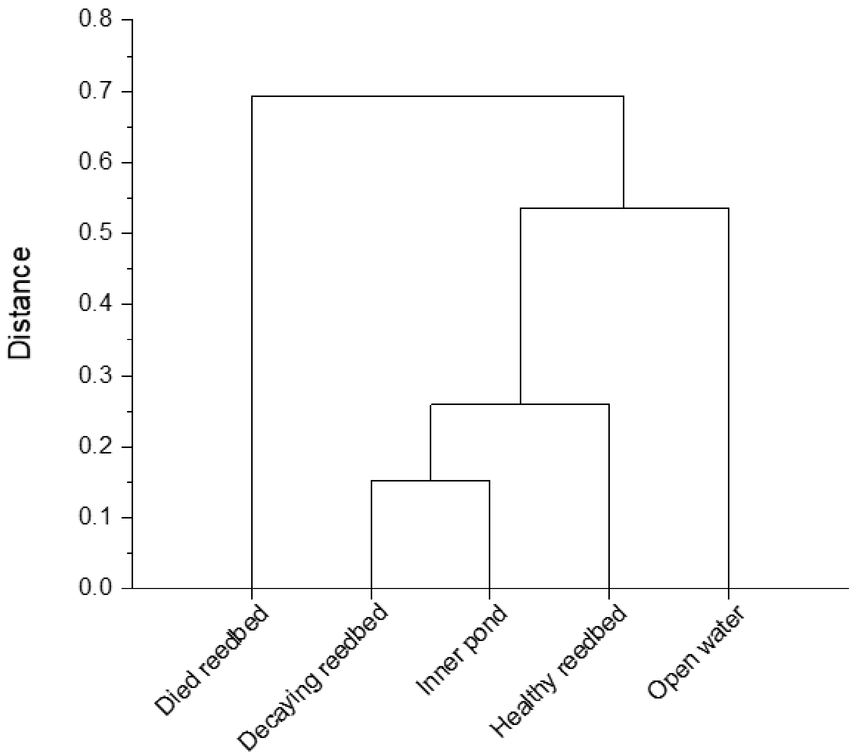


Figure 20: Similarity of the investigated habitats by phytoplankton community composition (clustering method: group average, correlation) in the Hungarian part of the lake.

There are some saline character species in the zooplankton community, which indicate the soda-saline chemical type of Lake Neusiedl / Fertő. For instance, the soda characteristic *Arctodiaptomus spinosus* can be found in the open water.

A non-linear relationship was detected between phytoplankton and zooplankton (Figure 21). Zooplankton was the most abundant in closed macrophyte-rich parts of the Hungarian belt, and in these waterbodies the zooplankton caused a strong top-down control on the phytoplankton.

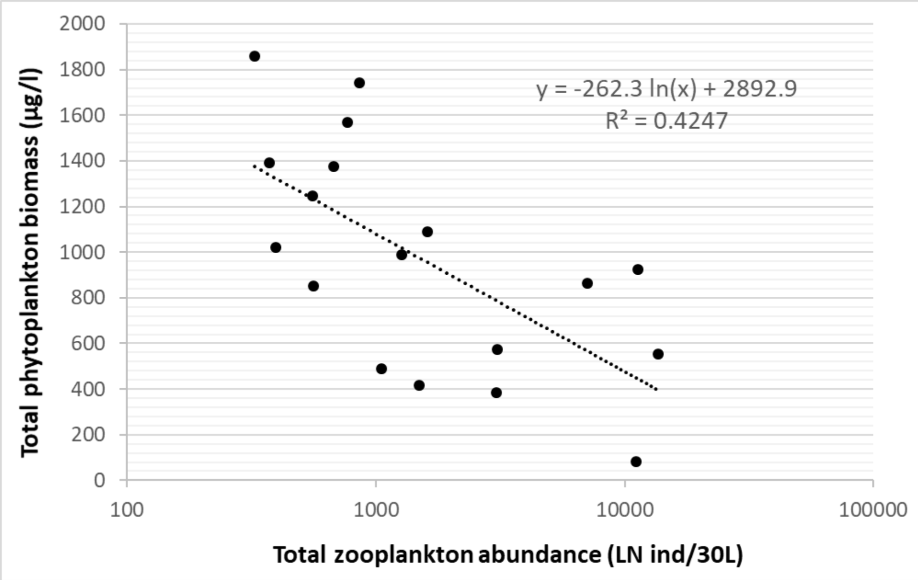


Figure 21: Relationship between zooplankton abundance and phytoplankton biomass in Lake Neusiedl / Fertő.

According to the quantitative survey of the submerged macrophytes, they have sometimes much less spatial cover than in 2019, but its spread-out may cause dense covering by fluctuation over periods, consequently they also have importance in lake management practice.

3.6 Reed structure and changes

The areal changes of the Hungarian part of the Lake Neusiedl / Fertő have been investigated in the frame of the REBEN project by using different data sources. The archive maps of the First (1785), Second (1845), Third (1882) and Reambulated Third (1920) Military Surveys were applied, along different aerial photographs (from year 1959, 1982, 1991, 1999, 2007, and 2017) as primary data-sources for this investigation. The results show that the reed area has been significantly increased on the Hungarian part from ~25% (but less than 1% for the current lake area) to ~84.6% till 1959, and the increase is much-much smaller after the water regulation (Figure 14), it increased to ~86% till 2017 (see Figure 22). This means 4.6 ha/year in the last 10 years (2007–2017).

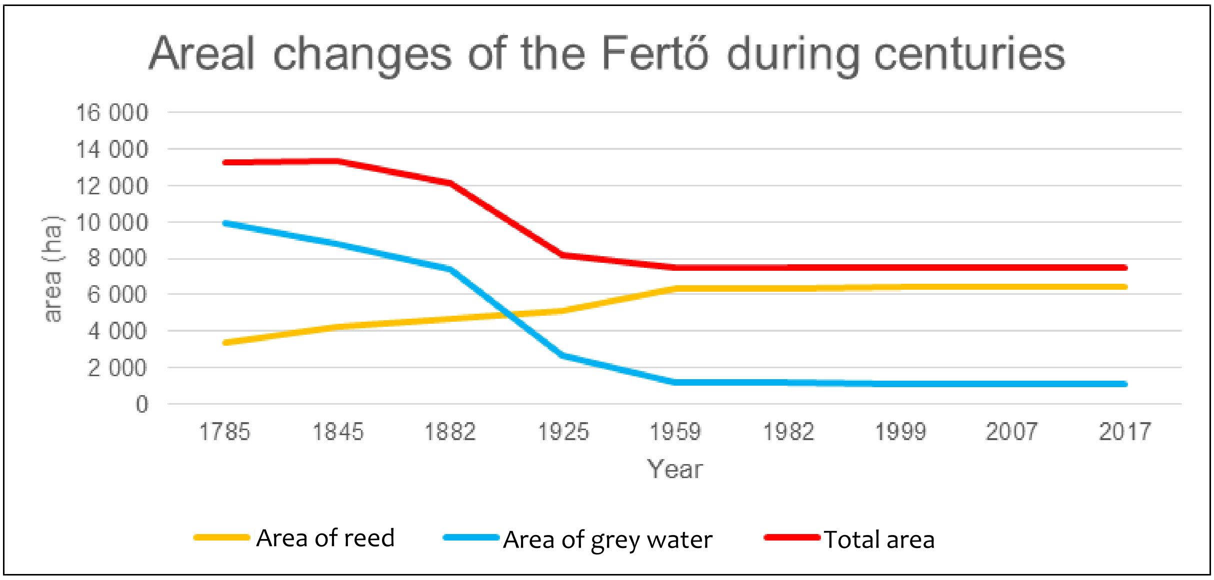


Figure 22. The areal changes of the Hungarian part of Lake Neusiedl / Fertő during centuries.

3.7 Long-term developments

The findings from the REBEN project are based on the experience of the last decades, and the considerations for further development also concern a period that can be described as "short to medium-term" and looks a maximum of 50 years into the future. Beyond that, however, long-term developments and trends are also of interest.

One aspect of the long-term development of the lake was investigated with the REBEN project: the silting up of the lake basin. Since a large amount of solid matter enters the lake every year or generates in it by precipitation and other processes, it is only a matter of time until the relatively shallow lake basin is filled up, not only considered in geological time periods. What can significantly reduce this process is a reduction of inputs and/or enforcement of sediment dredging. This concerns the aspect of sedimentation in the literal sense, quasi a "filling" of the lake basin by solids (see Figure 23 right). The sedimentation of the reed belt by increased reed growth, either by overgrowth of open reed beds and brown water areas in the reed belt, or by increasing the total area of the reed belt at the expense of the area of the open lake (see Figure 23 middle) is to be distinguished from this.

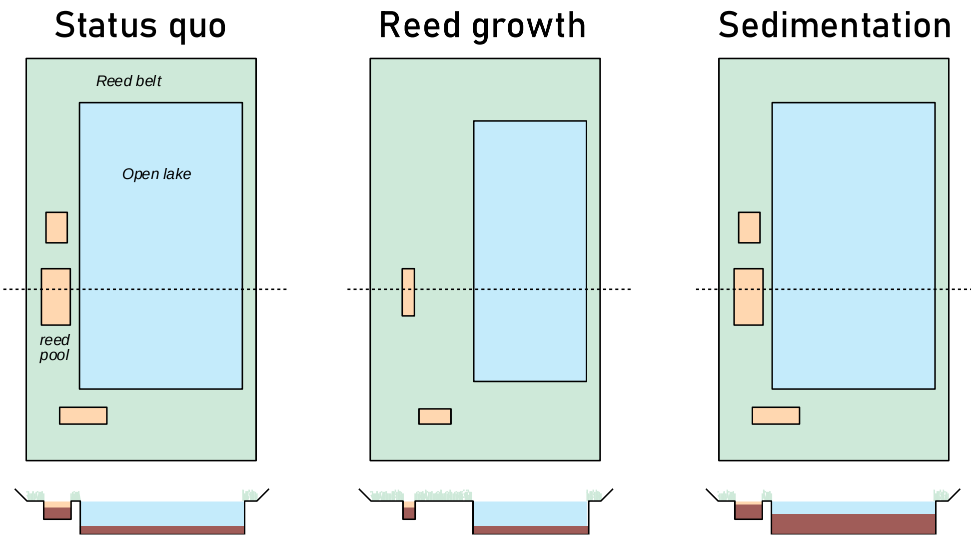


Figure 23. Schematic drawing of "Verlandung" in the sense of an increase of reed stands (middle) and of sedimentation (right).

The following scenarios attempt to disentangle these different aspects of sedimentation (for which unambiguous linguistic equivalents have not been found neither in German, nor in Hungarian or English), not least with regard to those water management objectives which address sedimentation and reed growth.

A second long-term aspect already mentioned in Report 1 "Hydrology" of the Austrian expert team is **global warming**. The investigations of Soja *et al.* (2014) show a noticeable shortening of periods of ice cover of the lake within the last 100 years (Figure 24), while Dokulil (2013) in his data analysis showed a significant summer temperature increase of the lake over the last few decades (Figure 25). Although the temperature variations over this long period are large, a connection with global warming from the second half of the 20th century onwards is obvious. Recent analyses from data collectors for the period 1976–2018 revealed a 1.9 °C increase of water temperature (Maracek & Sailer 2019).

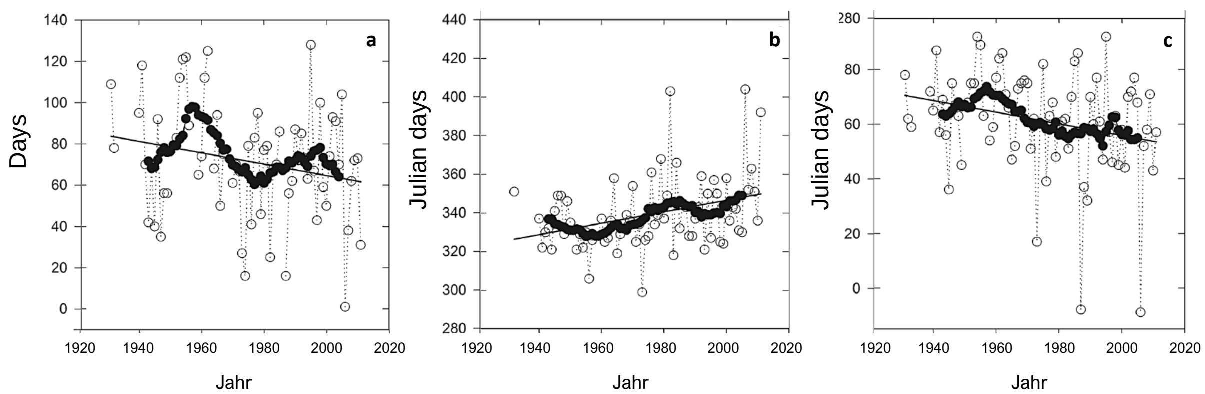


Figure 24. Change of the duration (a), the start (b) and the end (c) of ice cover in Lake Neusiedl / Fertő during the last 100 years (from: Soja *et al.* (2014)).

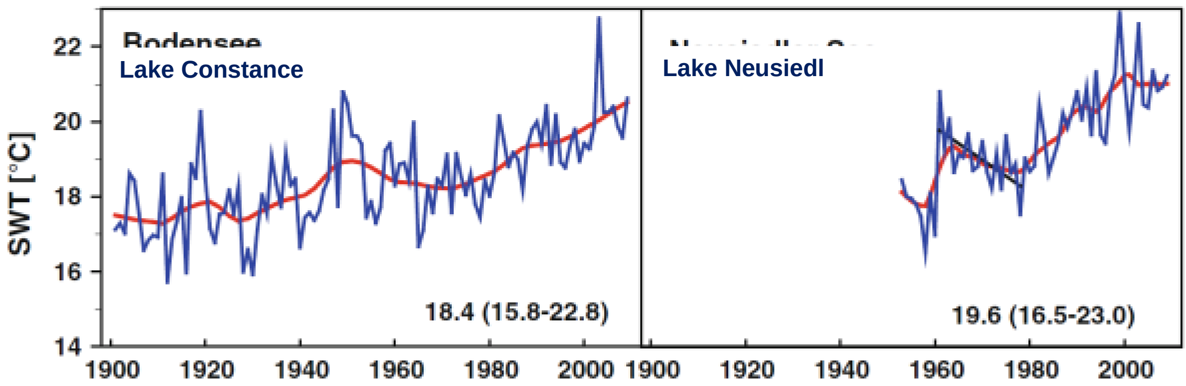


Figure 25. Increase of summer surface water temperature (SWT) of the deepest and the shallowest lake in Austria over the last decades (from: Dokulil (2013)).

As discussed in Report 1 "Hydrology" of the Austrian researchers, the investigations on climate change by Schöner *et al.* (2011) and Blöschl *et al.* (2018) point to a further increase in air temperature for the coming decades. According to Eitzinger *et al.* (2009), a tendency towards more frequent (or longer) dry periods is likely for the coming decades, which in the long term leads to expectations of decreasing water levels. According to Schöner *et al.* (2011), however, a predicted slight increase in precipitation in the east of Austria indicates that the losses might be compensated more or less and that the current state might remain approximately the same. Yet, associating analogous years in the past of Lake Neusiedl / Fertő with the future climate (Report 1 of the Hungarian researchers) indicated that the effect of climate change would likely lead to decreasing amounts of water discharged from the lake via the Hanság Channel.

A gradual increase in the concentration of water constituents is to be expected as water levels decrease, as was also shown by modelling the salt content during long dry periods. The climate modelling in Zessner *et al.* (2012)and the mass balance based on it (Wolfram *et al.* 2012) forecast an increase in the chloride concentration in the median from 246 mg L^{-1} (1992–2007) to 595 mg L^{-1} (500-year scenario). A similar increase is expected for sodium and (hydrogen)carbonate. The lake would take on more of the character of a true soda lake and thus approach the low-concentration salt pans of the Seewinkel area in its basic chemistry. Already now, the conductivity in the inner reed belt reaches more than 6 000 µS cm^{-1} in dry periods. In a long-lasting low water phase without discharges via the Hanság Channel such values will also occur in the open lake.

It is difficult to say whether the open lake would also change structurally (*e.g.*, through the penetration of submerged macrophytes or other reed species), but it cannot be excluded. A littoral bulrush presence may be a possible consequence of global warming and a signal of the first trends towards changes in Lake Neusiedl / Fertő. In the Hungarian part of Lake Neusiedl / Fertő, an increased penetration of the littoral bulrush (*Schoenoplectus litoralis*) has been observed in recent years. The biggest stable population of Lake Neusiedl / Fertő is at Kőbokor-tó, which is followed by Püspök-tó and Gémes-tó, and at least with the population at Hidegség-tó. A significant diversity was observed among different locations in the size, density, and inflorescence proportions of the patches (Szőke 2016).

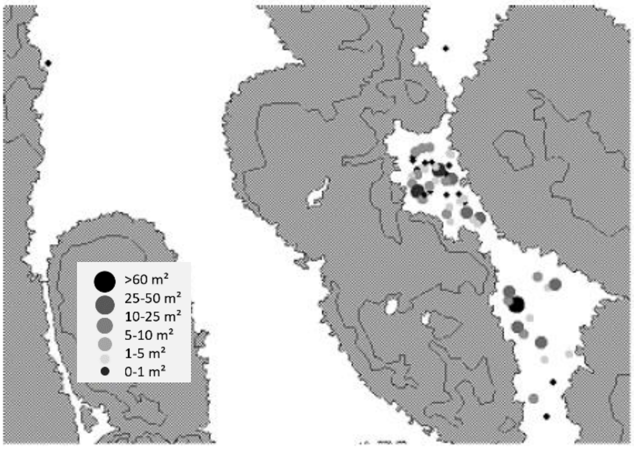


Figure 26. Distribution of the littoral bulrush *(Schoenoplectus litoralis)* in the southern part of the Bay of Fertőrákos (source: M. Pannonhalmi).

Figure 27. Distribution of the littoral bulrush *(Schoenoplectus litoralis)* near Búzaszem-bokor. Photo: Kalmár in Szőke (2016).

To a certain extent, the two long-term trends overshadow the scenarios described below. On a third level, measures must be taken into account to estimate future developments, which are largely excluded here and described in detail in the management plan.

4 SCENARIOS – DIFFERENT FRAMEWORK CONDITIONS

4.1 Definition of scenarios

In the following, we will describe how the processes and balance sheets described in the previous chapters could change under different conditions. The considered forecast period is in the range of a few decades.

It is obvious that these considerations are not the result of precise calculations but are strongly based on expert assessments. However, these are based on the extensive investigations and the resulting findings of the project REBEN. They reflect the current state of knowledge and can be regarded as "best guess".

In Chapters 3.2 & 3.3 the water level (and thus indirectly the climatic and meteorological conditions) and the structure in the reed belt (and here primarily the reed channels) were described as the most important factors for material transport. Therefore, it seems reasonable to also define the scenarios with changed conditions based on these two influencing factors. Three pairs of scenarios are distinguished.

4.1.1 Scenarios "Extreme water levels"

In the investigation period within the framework of the project REBEN, the water level of Lake Neusiedl / Fertő between 115.3 and 115.6 m asl (max. 115.5 m asl in the operation period of the online monitoring stations). For the conditions at very low or very high water levels, we rely on scarce experience from previous investigations (above all the material balance (Wolfram *et al.* 2012)). Nevertheless, these situations are of great interest with regard to possible changes in the course of a progressive global warming, but also with regard to a possible artificial water supply from external sources. Two scenarios are therefore defined:

- **Scenario P1** <115.2 m asl
- **Scenario P2** >115.8 m asl

Scenario P1 assumes that at a very low level there are still fluctuations in the water level. Concerning scenario P2 we have to add that only effects of high water level are considered, but not measures to reach this scenario (*e.g.* external water supply). Consequences however are considered (outflow over the Hanság Channel).

4.1.2 Scenarios "Different flow patterns of the river Wulka through the reed belt"

According to all information available so far (field observations, chemical analyses, water quality monitoring stations, tracer experiment, modelling) the flow of the river Wulka through the reed belt at low flows is mainly linear. Under flood conditions, however, the Wulka is likely to overflow and diffuse the reed belt. Two alternative scenarios are defined:

- **Scenario W1** only diffuse flow through the reed belt
- **Scenario W2** only linear flow through the reed belt

Scenario W2 (unlike scenario P2, see note above) requires substantial measures and interventions in the reed belt, which are therefore taken into account in the description and included in the subsequent assessment (Chapter 4).

4.1.3 Scenarios „Reed channels"

The findings clearly show that the channels are of great importance for the exchange between the open lake and the reed belt. On the basis of the existing network of channels and the assumption that they are in a proper status (not silted up or overgrown), it was estimated that 9 250 or 13 200 t of solids and 15 or 18 t (range from the mass balance over a longer period of time: 7 to 35 t) of phosphorus are transported annually from the open lake into the reed belt.

However, the point is not only the existence of channels but also the connected retention area behind. Here, four types of reed structure can be roughly distinguished. This classification was used only for the purpose of evaluating the scenarios in this report. Much more elaborated reed classification systems were developed for the Austrian part of the reed belt (Csaplovics & Schmidt 2010a; b) as well as for Hungarian lakes including Lake Neusiedl / Fertő (Márkus *et al.* 2008).

Almost half of the Austrian reed belt is very dense (type A) and at most crossed by channels (type B) with parallel dams. This part of the reed belt therefore offers poor retention area for water and mass transfer. In Austria, open areas are found mainly near Mörbisch and Illmitz, with smaller areas also at Rust and Jois. They were the focus of the REBEN studies and account for about 15% of the area of the Austrian reed belt. Most of these areas are currently well connected to the open lake (type D).

A special situation is represented by the measuring station IL9 at Illmitz Resort, which is not or hardly connected to the open lake (type C) and differs chemically and biologically from the connected areas further north (see Figure 28).

In view of these different characteristics of the reed belt, two scenarios can be defined:

- **Scenario S1** No channels or existing channel silted up or overgrown; existing channels are not connected to extended water areas, *i.e.*, the reed belt corresponds predominantly to type A, B and D (*cf* Figure 28)
- **Scenario S2** Enlargement of the existing network of channels and good connection to the inner areas of the reed belt, *i.e.*, the areas of type C are preserved and reed beds of type D are connected to the lake (-> converted to type C)

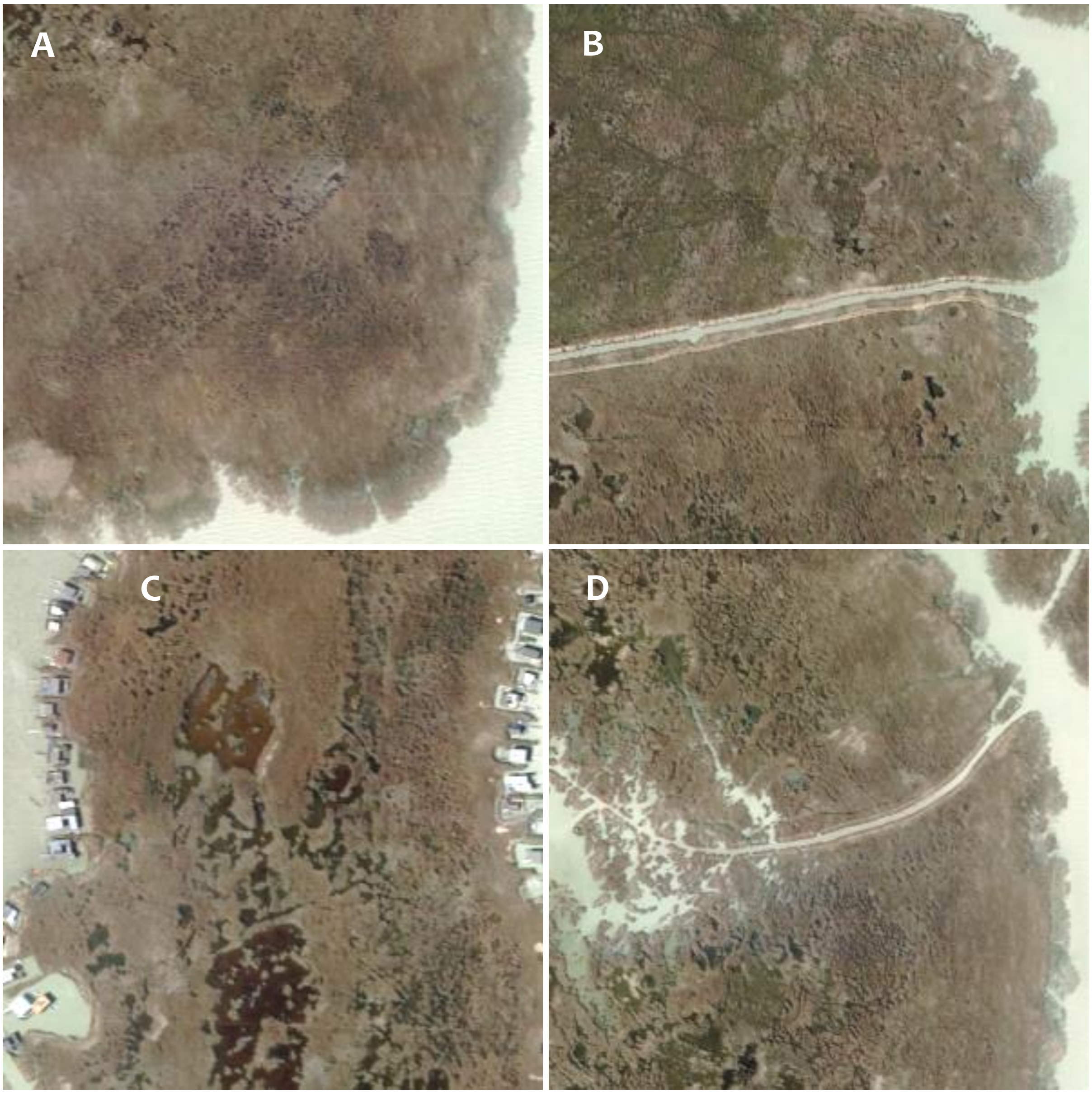


Figure 28. Different characteristics of the reed belt near Oggau/Rust. A: area with dense reed without pools and channels, B: area crossed by a channel without lateral connection, C: area with pools without connection to the lake, D: area with pools with good connection to the lake.

Like scenario W2, S2 is requires substantial measures and interventions in the reed belt. They must therefore also be taken into account in the assessment in Chapter 4. The measures are, of course, limited to Lake Neusiedl / Fertő outside the National Park, where no anthropogenic interventions are currently permitted in the conservation zone in the southern part of the lake. This also means, however, that there will be areas in the entire Lake Neusiedl / Fertő that are not connected to the open lake, even in scenario S2.

For the six scenarios, the gradients, exchange processes and loads shown in Chapter 3 are to be reassessed and described in the following. The forecasts represent the result of a well-founded expert assessment, which has been developed by the team of experts on the basis of extensive analyses and data evaluations (Reports 1 to 6 of the Austrian expert team) or the load estimates derived from them (Chapter 3.4 of the present report).

4.2 Scenario P1 – water level <115.2 m ü.A.

The scenario with a water level <115.2 m asl is not a purely hypothetical one, even though water levels were consistently higher during the period of the REBEN project studies. However, the authors can build on experience from 2003/2004, and even at the time of writing this report (August 2020), the average water level of the lake is below 115.2 m asl (https://wasser.bgld.gv.at).

Recent surveys have shown that at a water level of 115.2 m a large part of the reed belt is already dry. At 115.0 m asl, as last seen in autumn 2003, the entire reed belt is *de facto* dry, and the lake is reduced to the open water surface. In the Austrian part of the lake only very few channels are still navigable and available for a strongly limited water exchange. The incoming water, however, does not find areas deep enough to be flooded. This means that the water masses that are pressed into the few deeper channels, even during strong winds and seiche movements, are very small. This effect can be clearly demonstrated by means of Manning-Strickler modelling: The flow rate through a well investigated channel at Mörbisch decreases significantly with decreasing water level, *i.e.*, it requires ever stronger seiche movements and waves to be able to introduce water into the channel (Figure 29).

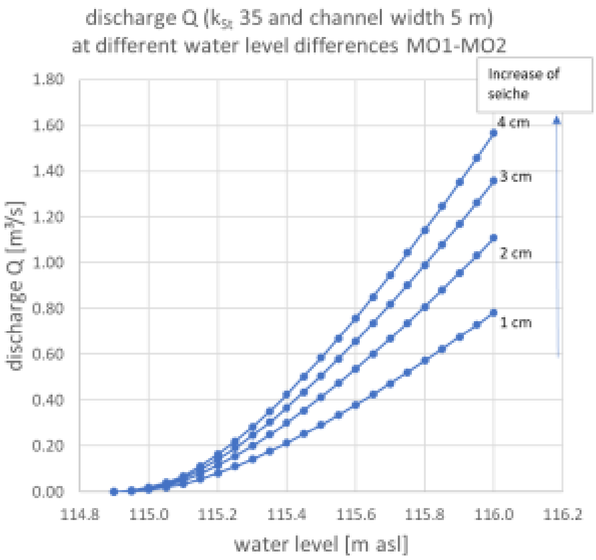


Figure 29. Relation between water level and discharge through a channel near Mörbisch assuming varying water level differences (MO1 lake edge, MO2 reed belt) resulting from a seiche wave (model after Manning-Strickler).

While the situation, as described, can be estimated relatively well for shorter phases of low water levels, the question of longer-term development (*e.g.*, several years with an average water level around 115.2 m asl and a minimum around 115.0 m asl) is less clear. The greatest uncertainty concerns the development of the reed belt. It is conceivable that plants other than phragmites will increasingly penetrate the semi-terrestrial area and spread to the high-lying areas (as can currently be observed on dams along channels). It cannot be excluded that regular drying of the sediment in the reed belt and increased contact with atmospheric oxygen may contribute to a changed (possibly increased) degradation of organic material. However, this assumption cannot be based on any findings or reliable evidence at present. Data from Hietz (1989) indicate even the opposite.

For the mass balance of the lake, it can be assumed that the inputs as well as the new formation of calcite sediment ("Kalkschlamm") in the lake will change only slightly, if smaller inflows of the Wulka are neglected and the low water level is considered as a result of lower precipitation or higher evaporation. At <115.2 m asl, however, no sedimentation area is available in the reed belt, *i.e.*, the introduced and newly formed sediments will mainly settle in the open lake near the shore and protected from the wind. This may enhance the need for dredging the marinas and bathing bays. Sedimentation zones in the southern part of the lake (national park) will however remain and get more extended.

An approximate estimate of the increased sedimentation in the open lake can be made based on the approximately 9 700 t currently being transported from the lake into the reed belt (estimated for the whole lake, Table 5). They correspond to a sediment volume of about 25 700 m^3, which, if evenly distributed over the area of the open lake (140 km^2), represents an annual sedimentation of 0.18 mm. If the sediment volume is related to an estimated 10 km² of bays and wind-protected areas, *i.e.,* potential depositional areas, the rate increases accordingly to just under 2 mm/a, *i.e.,* a few centimetres in 10 years.

Also for nutrients a significantly reduced export to the reed belt can be expected at low water levels, as already suggested by the mass balance of Wolfram *et al.* (2012). This will increase the nutrient concentrations in the open lake. Besides the reduced export of sediment and nutrients into the reed belt, an enhanced resuspension of particle-bound nutrients from the sediment in the open lake (due to the lower water depth) is likely to play a role. The increase of phosphorus concentration in 2004 showed this development in the beginning way. Impacts on the concentration of other substances are described in Chapter 3.7.

For those pollutants that are largely degraded or converted in the lake reed belt system, no clear estimation can be made for the low water level scenario. Since the degradation and conversion is partly photocatalytic, a continuation of the concentration reduction would be quite conceivable. Based on the current state of knowledge, it is not possible to predict whether an increase in turbidity due to the lack of discharge of solids into the reed belt would result in lower degradation rates and thus an increase in concentrations. The situation is different for substances that are largely persistent in the open lake (*e.g.,* PFOA or N,N-dimethyl sulfamide). If an unchanged input via the Wulka and other inputs such as atmospheric deposition is assumed and the falling water level results from an increased predominance of evaporation over precipitation, then an increase in the enrichment factor *(af)* and thus higher concentrations in the lake than at present can be assumed.

For the substances PFOS, fluoranthene and benzo(a)pyrene, for which the risk of an EQS failure cannot be excluded already at this stage, the situation is likely to deteriorate. On the one hand, a concentration of these substances also plays a role due to the excess of evaporation over precipitation. On the other hand, it can be assumed that the discharge and transfer of the two PAHs (fluoranthene and benzo(a)pyrene) with the suspended matter into the reed belt will not take place to the same extent. Thus, an overall increased concentration in the lake compared to today can be expected, even if the level of release and thus internal loading (*e.g.,* in the case of benzo(a)pyrene) would drop. For PFOS at present an adsorption to the reed sediment might cause a reduction of the concentrations in the lake. This could become ineffective in case of long-term low water levels and without water exchange with the reed belt. Thus, PFOS concentrations are expected to continue to rise in the event of long-term low water levels. For dissolved lead, the risk of failure to meet the environmental quality standards must be taken into consideration. Adsorption and sedimentation as well as desorption and mobilization from the sediment also play an important role here. In addition to a current discharge with solids into the reed belt, the data for lead and other heavy metals indicate that adsorption in the reed belt currently also outweighs the mobilization of dissolved metals and a lack of connection to the reed belt is likely to increase the concentration of dissolved lead in the lake. The scenario under consideration should therefore increase the risk of failing to meet the environmental quality standards (EQS) for the substances discussed.

From a limnological point of view, scenario P1 would probably initially lead to a decrease of biodiversity since the aquatic habitats were lost when the reed belt dried up. This would affect the local communities (among the fish, *e.g.*, the crucian carp), but also species that regularly migrate from the open lake into the reed belt. However, if the salinity increases (see above), specialists such as those currently found in the salt pans in Seewinkel could benefit and increase in abundance. The aquatic biocoenoses would also experience a (natural) shift in the species composition if the low water level persists for a long time, which can be seen as ecologically positive as long as the variability of the water level is maintained – even if at a low level.

In summary, the expected changes for the development of suspended matter and nutrients are shown in simplified form in Figure 30. Arrows stand for loads, where the line thickness correlates with the load. Boxes represent storages/deposits or concentrations. In the upper half of the figure, the sediment is shown, with brown arrows indicating the transport of solids and beige arrows indicating the formation of new solids. In the lower half of the figure the mass fluxes for phosphorus are shown. Brown arrows represent the particulate fraction, blue arrows the dissolved fraction. The left column contains the status quo for solids and phosphorus, the right column the change according to the scenario. Changes of the loads are indicated by changes of the arrow thickness, changes of the concentrations in the storages/depots (as rectangles) are shown in different colours (orange ... increasing, green ... decreasing, grey ... constant).

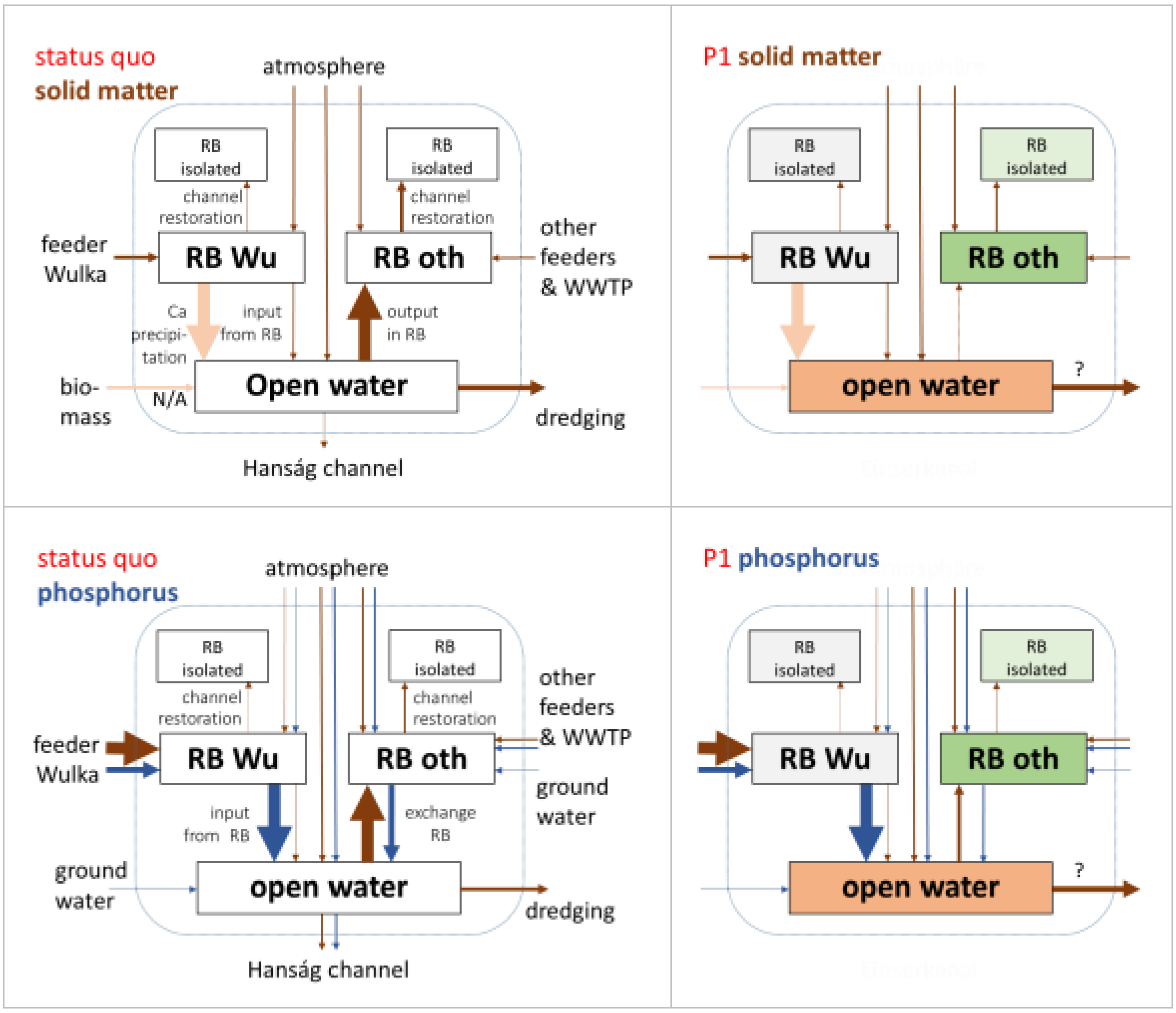


Figure 30. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario P1.

4.3 Scenario P2 – water level >115.8 m asl

There is also experience from the last decades for high water levels. In the mid-1990s, Lake Neusiedl / Fertő reached a peak of almost 116 m asl which resulted in massive discharges via the Hanság Channel. Subsequently, the problem of high salt discharges was addressed for the first time (Wolfram *et al.* 2004a). The effects of possible changes in the basic chemistry of the lake at high water discharges are therefore to be considered in this scenario. In addition to the changes in the lake itself, the balance element of the suspended matter discharge via the Hanság Channel is also influenced in this scenario.

Basically, the changes described in the previous scenario are opposite or reversed to those at high water levels. Irrespective of the question of channel maintenance (see below), the (open) channels are navigable at high water levels and allow an effective water exchange between the open lake and the reed belt (see Figure 29). It can also be expected that the "range" of the waves and seiche movements is greater than at medium water level. A small part of the water loads into the reed belt will be diffuse, at least in the area adjacent to the open lake.

The increased water input into the reed belt leads to increased input of suspended matter. It seems very likely that this will continue to be primarily via channels. In the area close to the lake, however, the area of the lake dam will certainly be reached, which will subsequently "grow" – an effect that does not occur at low water levels or only to an irrelevant extent. In general, however, from today's point of view it is rather unlikely that the diffuse inflow into the reed belt will contribute significantly to the overall load (as it probably still did in the 1980s).

Effects on sedimentation areas in the open lake are difficult to assess. These are always subject to interplay of erosion and sedimentation, and it is conceivable that with higher water levels and newly available sedimentation areas, the resuspension in the open lake will decrease. However, this hypothesis cannot be verified at present; not least in view of the difficulty of conclusively interpreting the available images of the sediment surface alone (see Report 2 "Reed" of the Austrian expert team). In any case, a high discharge of sediments from the open lake into the reed belt is to be expected. Also, as a result of discharges, there is an export of suspended matter from the entire lake system towards Hungary.

As regards dredging of marinas and bathing bays, it is possible that these are perceived as less urgent when water levels are high. Corresponding activities of the municipalities could therefore be temporarily reduced. However, they would probably be intensified again after a certain period of time, during which the sediment landings in the still-water areas of the marinas and bathing areas would continue to increase. The available data on dredging since 2004, however, do not show a correlation between water levels and sediment removal.

For nutrients (phosphorus) a similar development as for solids can be expected. With the discharge of suspended matter from the open lake, there will also be an export of nutrients, which will result in correspondingly lower concentrations in the open lake. The resuspension of sediments from the lake bottom will also decrease at a water depth of >2 m, although the lake will certainly retain its typical turbidity even at high water levels. Overall, however, a noticeable decrease of phosphorus concentrations in the open water is to be expected at high water levels, primarily due to nutrient discharge into the reed belt, as could already be observed in the mid-1990s (see Fig. 45 in Report 3 of the Austrian researchers).

For the pollutants, too, the changes described in the previous scenario are opposite or reversed to those at high water levels. Thus, it can be assumed that at higher water levels and increased discharge via the Hanság Channel, the accumulation of persistent substances in the lake *(af)* is reduced. Furthermore, an increased connection of the reed belt and the resulting increased discharge of solids from the lake also leads to an increased discharge of particle-bound pollutants such as PAH or metals or to a potentially increased adsorption of dissolved pollutants on sediments in the reed belt. The extent to which the increased connection of remote reed areas due to high water levels will result in increased mobilization and internal loading of the lake cannot be estimated at present. Overall, however, it is to be expected that in the case of the scenario of long-term high water levels the risk of failing to meet the EQS for the substances under consideration will be reduced as long as the reed belt is well linked with the open lake.

A steady high water level is also potentially serious for the basic chemistry of Lake Neusiedl / Fertő. According to the current weir operation regulations, from November to January, from a water level of 115.70 m asl up to 15 m^3/s are discharged via the Hanság Channel, from April to August up to 6 m^3/s. In the months in between, the limit water level shifts gradually; the discharge volume is then up to 6 m^3/s in February and March, and up to 15 m^3/s in October. The water level targets aim at the protection of infrastructures in the lakeshore area, which would be endangered at higher water levels in case of strong winds or short-term precipitation-induced rise of the water level (see Figure 31).

The currently valid weir regulation therefore means that in scenario P2 at >115.8 m asl a quasi-permanent discharge of lake water would be necessary. The effects of frequent discharges on the salt balance – concretely: the risk of reducing the salinity of the lake – were discussed in detail by Wolfram *et al.* (2004a) and are manifold: from the risk of increased eutrophication to the loss of the typical biocoenosis of the soda lake. These consequences of a high water level in scenario P2 will not be discussed further here, but they make clear that a realization of scenario P2 is only possible with an adjustment of the weir operation regulations (involving flood protection measures for sensitive infra-structures).

Figure 31. Flood situation at the bathing resort of Illmitz on 9th March 2009 (photo: M. Pannon-halmi).

Irrespective of the considerations for water level regulation and an adjustment of the weir operating regulations, a stronger lateral network between the open lake and the reed belt as well as into the offshore meadows beyond will be present in any case at high water levels, which has both chemical and ecological effects, *e.g.*, the use of shallow water areas as spawning grounds for fish. In the long term it is to be expected that the increasing rise of the lake dam will again limit the diffuse flow through the reed belt. Also, the question arises, how long and how much sedimentation the reed belt can "stand". The following numbers can give an orientation:

The input of about 7 555 t/a of suspended matter into the reed belt (Austria only) results in a volume of about 20 000 m^3 – taking into account the figures and assumptions regarding water content and density as stated in the Report 2 "Reeds" of the Austrian expert team. In relation to the Austrian area of the reed belt (102 km^2) this would correspond to an annual increase of 0.2 mm. Related to the total (11.7 km^2) or well-connected water areas (5.7 km^2) in Austria according to the reed water GIS layer, the sedimentation rate would be 1.7 or 3.5 mm/a and thus several centimetres in 10 years.

In summary, the expected changes for the development of suspended matter and nutrients are again shown in Figure 32. For explanation of the symbols see scenario P1.

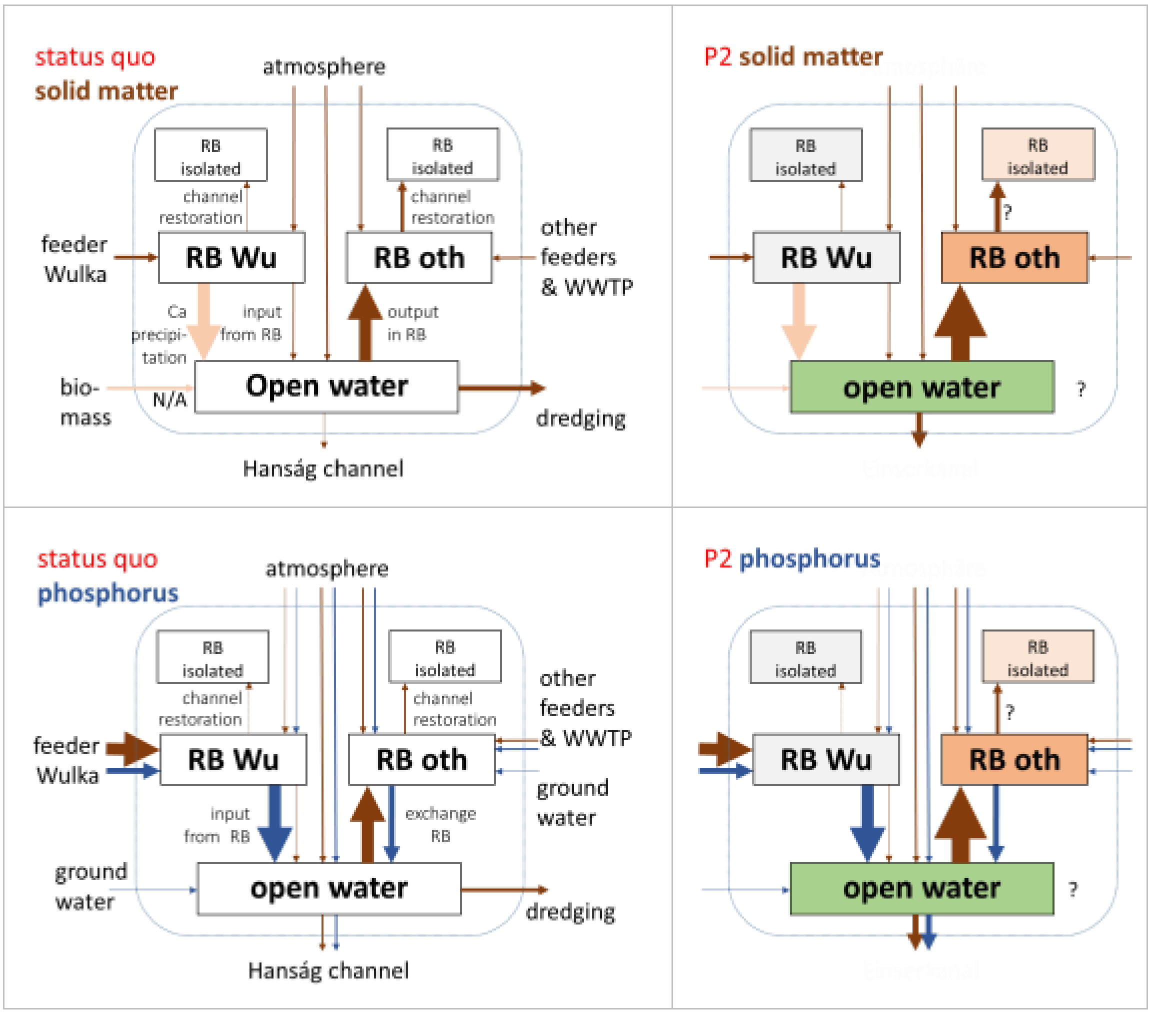


Figure 32. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario P2.

4.4 Scenario W1 – diffuse flow of the river Wulka through the reed belt

According to the available chemical analyses, on the basis of observations in the open land and according to the available findings from the tracer experiment, the Wulka flows on its way through the reed belt at low water mainly through an existing channel system, which, however, silts up relatively quickly through reed and other plants. In recent years, it has been necessary to restore this channel system frequently, most recently in 2018 and thus during the life of the REBEN project. At the beginning of the project, a major part of the Wulka water might have flowed diffusely through the reed belt and reached the channels only after a certain delay. During floods, the hydraulic capacity of the channels is too low; in this case the Wulka flows mainly diffusely through the reed belt.

Scenario W1 assumes that the channels in the Wulka estuary are no longer being restored and that even a low water discharge must first diffusely find its way between the reed stalks to the main channel and to the mouth into the open lake. It can be assumed that the dense reeds not only cause a significant reduction of the flow velocity, but also a tailback, which causes a slight increase of the water level in the area of the Wulka estuary. Due to the lack of geodetic data on the bed elevation in the reed area and in the channels, more precise information is not possible.

As can be seen from the mass balance in Table 4, this change in the flow rate will have little effect on suspended matter input, since a large part of the annual load (which is mainly transported during floods) remains in the reed belt of the Wulka. However, a tendential increase of the retained freight is likely. Here, the question inevitably arises as to how long the deposition of an average of about 3 800 t of solid matter per year (as dry matter, corresponding to about 10 000 m^3 of wet volume) in the Wulka estuary be possible in view of the increasing silting-up. Related to a reed belt of about 10 km^2, the sedimentation rate is 1 mm/a. Depending on the assumption of the actual retention area, it is more likely to be 2 or more mm per year or several centimetres in 10 years. The potential to take additional solids is therefore likely to be exhausted in the foreseeable future. However, the "life span" of the reed belt at the Wulka estuary can be extended if the annual solids load is reduced, *e.g.,* by erosion control in the catchment area, and/or an effective retention of suspended matter is ensured before entering the reed belt, *e.g.,* in a retention basin. Of course, the accumulating amount of solids would have to be regularly removed from this retention basin.

The same applies to phosphorus as to suspended solids. The particle-bound phosphorus is retained for the most part in the reed belt when the flow is predominantly or exclusively diffuse. However, an increasing release of dissolved phosphorus can also be assumed, which subsequently reaches the open lake (see Austrian Report 3 "Chemistry": data from the sampling site WU3). On the basis of the available data, the portion of total phosphorus reaching the open lake after flow and transformation in the reed belt was estimated to be just under 80%, probably less in flood years (around 60%). At present, the data do not give reason to assume a higher retention rate for total phosphorus with increasingly diffuse flow through the reed belt. However, this assumption is uncertain due to the structural complexity and knowledge deficits regarding the conversions in the dense reed belt. It is possible, for example, that predominant flow paths could establish without the need for channel restoration, in which a higher flow rate and better oxygen supply prevail, so that anaerobic conversion processes play a negligible role.

It is assumed that this scenario would not have a significant impact on the pollution of the lake and thus on the risk of failing to meet the EQS. Largely persistent substances, which are predominantly transported in dissolved form (*e.g.*, PFOS or PFOA), are likely to pass through the reed belt of the Wulka largely unchanged, as in the case of this scenario. For predominantly particulate-bound substances such as the PAHs benzo(a)pyrene or fluoranthene, the particulate fraction is separated to a high extent and, as already described above, no major change in solid retention can currently be observed. In the case of metals such as lead, a similar behaviour to that of phosphorus can currently be observed. Retention of particulate lead is opposed by a mobilization of dissolved lead. Whether the scenario considered here would result in an increased dissolution of lead cannot be estimated at present.

Concluding, the effects of a predominantly or exclusively diffuse flow through the Wulka reed belt must also be evaluated with regard to the biocoenoses. As the surveys in the REBEN project showed, the mouth area of the Wulka represents a hotspot of high ecological and nature conservation value. In the reed belt fish species of the Wulka system could be detected as well as purely stagnophilic species, including those that had not been detected in the lake for years or decades (*e.g.*, bitterling, crucian carp). The reduction of the flow paths of the Wulka to very small channels would presumably constrict the habitat of these species or at least limit it to the section close to the Wulka, because here – In the transition from the river to the reed belt – estuary-like conditions and high diversity in structure would probably continue to exist even without maintenance works.

A summary of the changes for the development of suspended matter and nutrients is shown schematically in Figure 33.

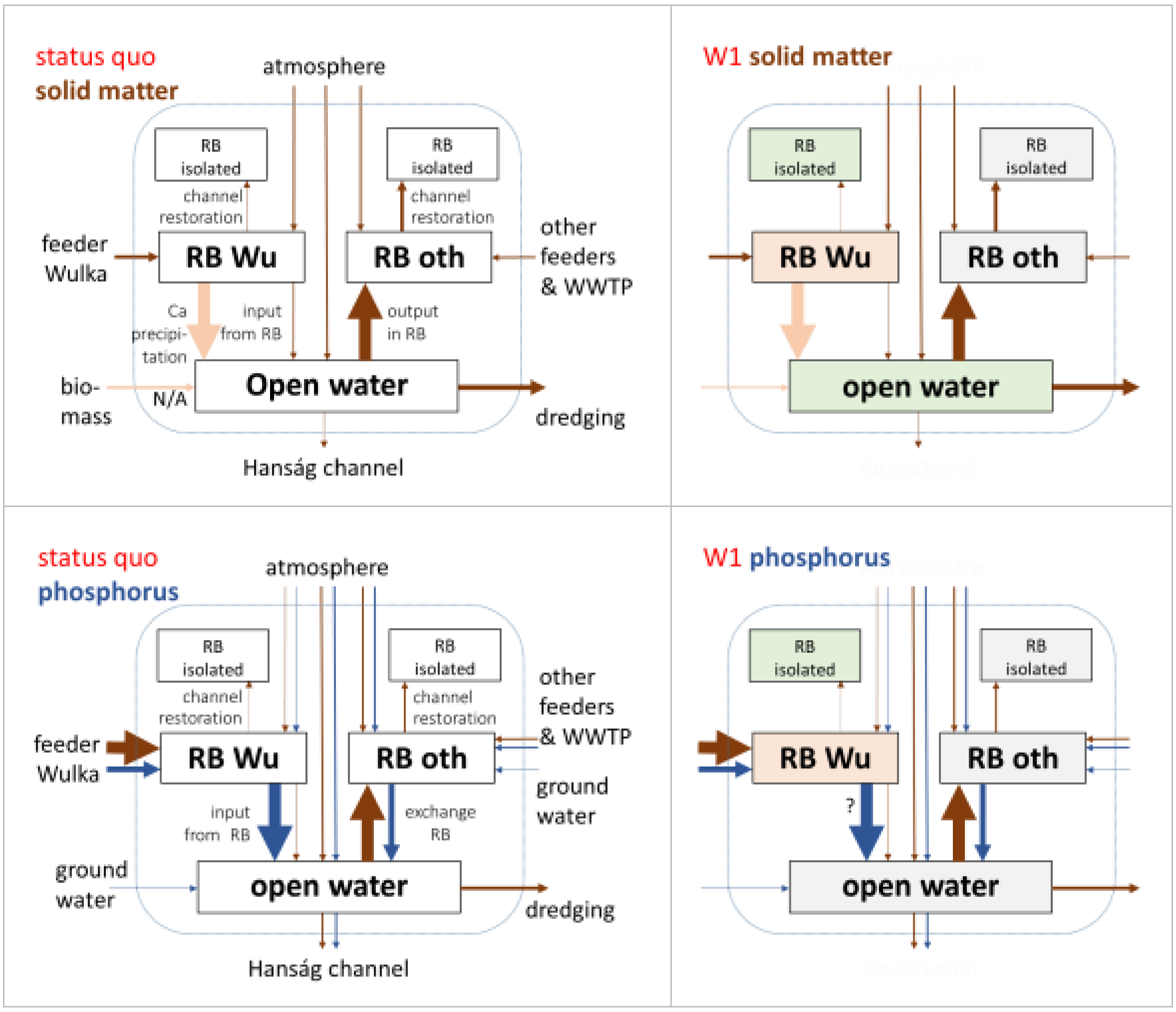


Figure 33. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario W1.

4.5 Scenario W2 – linear flow of the river Wulka through the reed belt

The scenario for the linear flow of the river Wulka through the reed bed is to be assessed first of all according to the extent to which it is possible from a hydraulic point of view. Despite the great uncertainties of the hydraulic modelling due to the lack of data on the terrain model of the reed belt, it is to be assumed that even with regular maintenance works, the existing channels are too small to be able to discharge discharges that are significantly above mean water. In any case, however, during high water the river Wulka overflows and currently flows diffusely through the reed belt.

A predominantly linear flow would therefore require enhanced hydraulic capacity of the channels, either by dredging additional channels or by widening the existing channels considerably. However, this would give rise sedimentation and reed growth, and make more frequent restoration activities necessary. Subsequently, it would have to be clarified whether the dredged material (rhizome, reed stalks, Wulka sediment) would be deposited on site or removed. The latter seems hardly feasible for cost reasons. However, on-site deposition in separated sedimentation zones in the reed belt could be an alternative to the current practice (deposition along the channels).

From these considerations it becomes clear that the scenario W2 would have to be specified with further assumptions and is realistic only under certain prerequisites. If one accepts these however as given and realizable, then the scenario would have without doubt noticeable influence on the sediment and nutrient balance.

For the solids in scenario W2 an increase of the load entering the open lake would follow. The coarser parts (silt to sand) would probably be deposited to a large extent in the north of the lake, the finer parts would be eroded and transported further. They will then change the balance element “dredging ports” or “internal transport and load”. The extent to which the solids from the river Wulka in scenario W2 reach the open lake depends on flood events. If these are also to be channelled through the reed belt, this would probably only be possible by designing a flood channel accordingly, *e.g.,* by raising and securing the lateral dams.

In the case of low water, the amount of sediments to be dredged in the area of the Wulka reed belt would have to be significantly increased in order to avoid sedimentation and reed formation in the channels and keep the W2 scenario conditions. In return, the sedimentation rate in the dense reed belt would significantly drop.

A reduced retention of the particulate fraction would also affect phosphorus; in addition, dissolved phosphorus would be released to a lesser extent. Since an exclusively linear flow through the reed belt is no longer possible during heavy floods, a diffuse flow and thus a discharge of dissolved substances from the reed belt would occur only rarely. On average over a longer period, this discharge would probably be lower than at present but unevenly distributed over time and should be understood as a "rare peak load".

A greatly reduced retention of solids in the Wulka reed belt, as expected as a result of these scenarios, would also have a significant impact on the lake's exposure to pollutants that are predominantly transported in particulate form and currently retained in the reed belt. Among the substances under consideration for which there is currently a risk of EQS failure, the PAHs benzo(a)pyrene and fluoranthene are particularly noteworthy. For these substances, the implementation of this scenario would increase the risk of missing the target. In addition, the risk that larger dredging measures for channel restoration could lead to exceeding the limits would have to be considered: Excavation and relocation of large amounts of sediment has the potential for an increased release of pollutants from the sediment and thus to cause an increase of the concentrations in the lake. The quantitative extent of such an internal load cannot be determined at this time. Appropriate monitoring measures would have to be provided in case of extensive dredging measures.

The effects of an exclusively linear flow through the reed belt on the communities in this hotspot would certainly strengthen the connectivity between river and lake and the exchange of the communities, especially in the course of floods under the assumption that these reach the lake more quickly and thus not only lead to a more intensive material input, but also to a drifting of riverine species into the lake. The access to the Wulka system would in any case improve for fish and other mobile species. It seems very probable that the Wulka would be used by some fish species as spawning grounds, *e.g.,* white bream or bleak. In addition, a temporary penetration of rheophilic to current-induced species (chub, gudgeon, barbel) into the lake can be expected. Overall, this would undoubtedly bring the lake closer to its fish-ecological reference state(*cf* Zick *et al.* (2006), Wolfram *et al.* (2008), Wolfram *et al.* (2018).

A crucial factor, however, would be the oxygen concentration, which can currently drop to 0 mg L^{-1} in the Wulka channel at the mouth of the open lake in midsummer overnight. This indicates a longer residence time in the reed belt, during which the oxygen introduced via the Wulka is completely consumed due to the decomposition of organic substances. A purely linear flow suggests that such oxygen extremes do not occur even in low-water situations and that the Wulka is therefore also usable as a habitat for rheophilic and oxygen-sensitive species along the entire flow section until the lake.

For stagnophilic species such as the mudminnow, the crucian carp and the bitterling, a purely linear flow through the reed belt could result in a restriction of their habitat. However, it can be assumed that in this scenario, too, areas will be preserved that can serve as habitat for the species mentioned. This also includes areas with very low oxygen concentrations where the mentioned species have a competitive advantage over others.

In summary, the changes for the development of suspended matter and nutrients are shown in Figure 34.

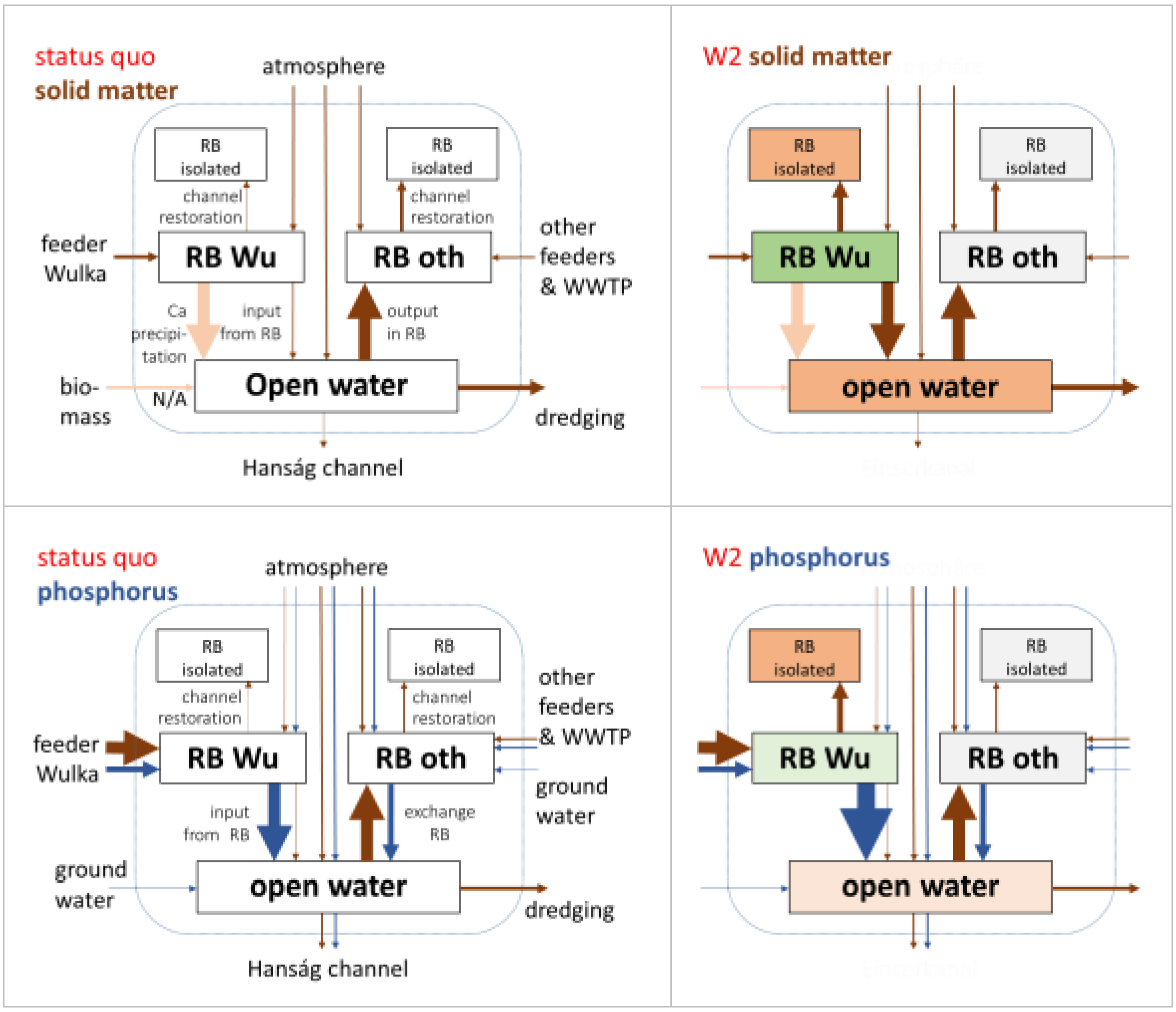


Figure 34. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario W2.

4.6 Scenario S1 – no reed channels

Our knowledge about the water exchange between the open lake and the Austrian reed belt, which is given in the presence or absence of reed channels, is not least a result of the difficulties in creating the digital terrain model for the three test areas. Depending on the chosen terrain model, the results of the hydraulic modelling differed considerably. They showed very clearly the serious effects of a narrowing of channels on the water exchange. In the Illmitz area, for example, flow velocities of several decimetres per second were observed during the event-related series of measurements in the fall of 2019 ("wind event", see Report 5 of the Austrian expert team) and from these, flows of several 100 L/s within an inflow and outflow cycle through a channel were derived. The first hydraulic model calculations resulted in flow velocities and flow rates that were one to two orders of magnitude below these values. The cause was channel constrictions in the digital model, in one case a completely "closed" channel (towards Ruster Poschn). This illustrates the enormous importance of the channels as transport routes into the reed belt today. Similarly, a significant influence on the water exchange could be demonstrated in Mörbisch with different assumptions about the width of channels.

Another point, which could not be quantified, is the higher evaporation, in case of a more frequent exchange between open lake and reed belt, which can lead to significantly enlarged, very shallow water areas in the inner reed belt that are inundated only for a short time. Scenario S1 prevents this effect. A reduced lake – reed belt exchange could be more important for the overall water balance. In other words, scenario S1 supports scenario P2 (high water level) in a certain sense.

This aspect aside, scenario S1 focuses on the effects on the water exchange between the lake and the reed belt, which would largely cease almost to zero without regular reed channel maintenance. The lake dam is now so high that at low water levels no water at all is transported into the inner reed belt. But even at medium-high water levels above the upper edge of the lake dam, the water exchange between the lake and the reed belt is negligible due to the very high hydraulic roughness of the area near the bottom in the dense reed beds. Only at a significantly higher water level, a certain flow is possible in areas with a loose stock of reed stalks, but even then it remains far behind the effective exchange through the channels. The wide reed channels act as "highways" for the rapid exchange of water between the open lake and the reed belt, while the network of very small and narrow spaces between the reed stalks is more like the crooked and winding streets of an old town.

Today, it can be assumed that the scenario S1 without reed channels largely prevails in the southern part of the lake in the area of the Austrian National Park. South of the road to the marina of Illmitz there is already an area without connection to the open lake. The conditions prevailing there were hydrochemically and biologically documented in the REBEN project with the sampling point IL9.

The consequences of a lack of the water exchange for the internal transport of substances within the lake are obvious. No notable changes are to be expected on the input side or with regard to new formation through precipitation of calcite. On the discharge side, however, the channel maintenance works, which lead to lateral sediment depositions, are stopped ("reed belt decoupled" in Figure 15). Above all, the sediments brought into the lake and newly formed in the lake remain in the open lake part and can only be deposited in calm bays or leeward of larger reed islands (*e.g.,* in view of prevailing NW winds at the southern edge of the Great Reed Island). For the open lake this means an annual accumulation of solids of about 10 000 t (which might lead to intensified dredging in marinas). Related to the entire open lake this would correspond to an annual sedimentation rate of 0.2 mm. If, however, the potential deposition areas are limited to about 10% of the lake, the expected sedimentation rate there increases tenfold accordingly – extrapolated over 10 years, this would result in a local increase of 2 cm. Conversely, the sedimentation rate in the reed belt would naturally decrease accordingly.

In the phosphorus balance, the same items are affected as in the sediment balance. However, it cannot be assumed that the deposition is permanent, as is the case with solids. The phosphorus introduced as particulates is initially deposited as such but can be released again in dissolved form via biological cycles. Both in dissolved and in particulate form (potentially with increased load of suspended matter), phosphorus will in any case lead to a measurable increase of the total phosphorus concentration in the open lake. The extent to which this development will be reflected in increased production cannot be plausibly estimated due to other limiting factors besides nutrients (especially light). In the long term, however, a deterioration of the water quality in the broader sense cannot be excluded.

For the concentration of pollutants, this scenario would have no expected effects as long as the water balance (lower evaporation) is not affected. Apart from that, however, this scenario would have to be evaluated same as to scenario P1, where the connection of the open lake to the reed belt is lost due to low water levels: Due to the missing discharge of sediment from the open lake to the reed areas, more pollutants remain in the lake. No more discharge of dissolved pollutants by adsorption to the reed sediment will occur. On the other hand, pollutants will not be released from the reed sediment into the open lake. Nevertheless, the risk of missed environmental objectives is expected to increase, since the discharge of solids is currently (= status quo) expected to outweigh a reduced net mobilization (in scenario S1).

For the aquatic biocenoses, the decoupling of water areas in the reed belt from the open lake partly corresponds to a loss of habitat. In the interior of the reed belt, specialized species that tolerate the conditions there (*e.g.*, mudminnow) could benefit. For species of the open lake that prefer to live in the outer reed belt or use the land-based offshore meadows as spawning ground (*e.g.* wild carp, see Herzig *et al.* (1994), Wolfram *et al.* (2004b)), the elimination of migration corridors would have a negative effect.

In summary, the changes for the development of suspended matter and nutrients are shown schematically in Figure 35.

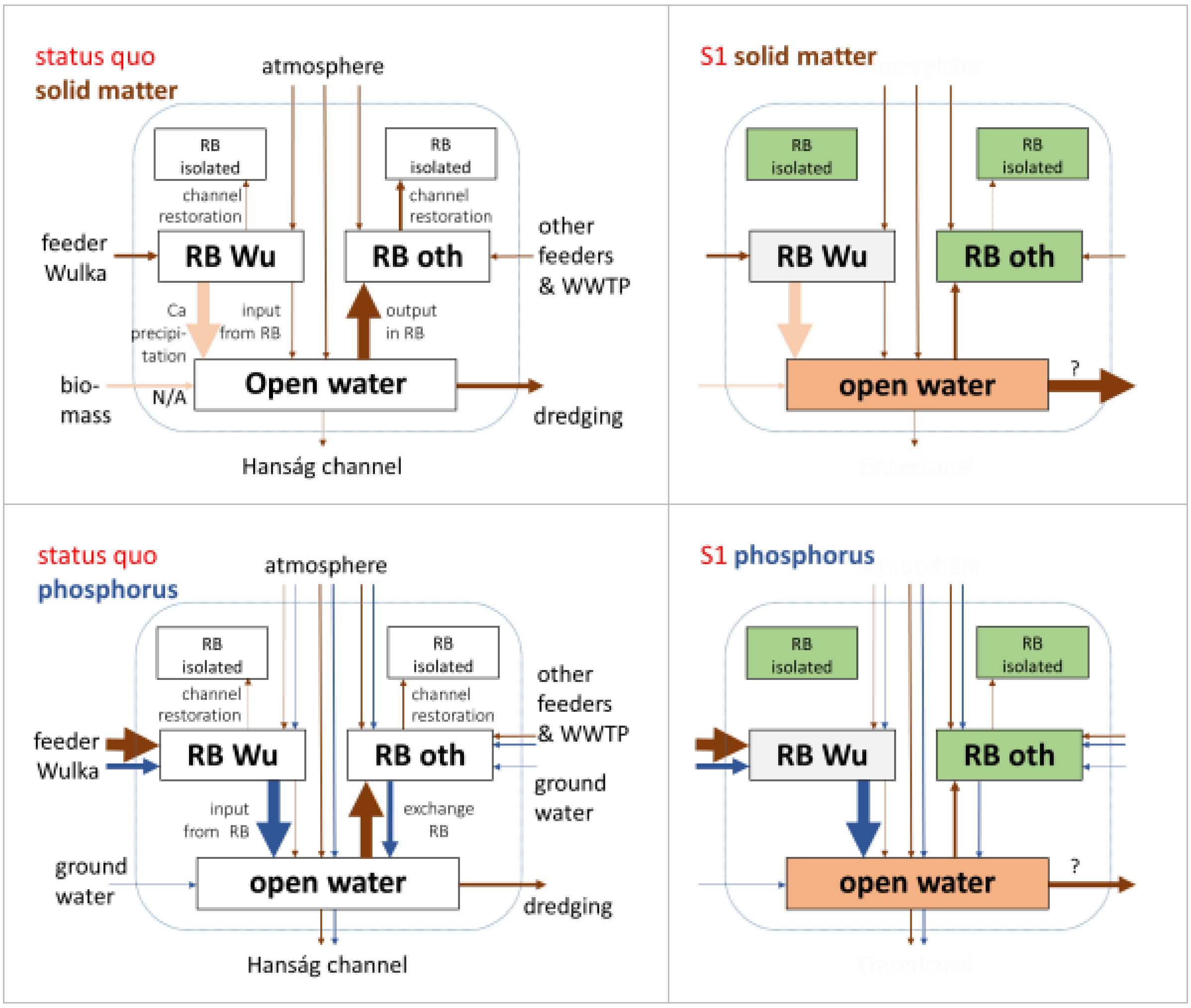


Figure 35. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario S1.

4.7 Scenario S2 – extended network of reed channels

As with the previous pairs of scenarios, S2 is also contrary to the previously discussed scenario S1. Currently, the situation at Mörbisch corresponds to this scenario, since there are numerous reed channels that have been maintained in the last years (see Report 2 "Reed" of the Austrian expert team). The area of Illmitz north of the Resort also resembles the image of a reed belt well connected by channels, although there is certainly still potential for more channels[1].

As explained in detail, the water exchange between the lake and the reed belt takes place predominantly via a broad network of channels; the diffuse inflow through areas of the reed belt close to the lake is negligible at average water levels. An enhancement of the system of reed channels would therefore improve the water exchange between lake and reed belt[2].

In this scenario, there would be no changes in the solid mass balance on the input side and with regard to sediment formation. However, an intensified exchange between the open lake and the reed belt would have a decisive influence on the lake-internal transport of solids. With regard to the sedimentation problem, scenario S2 brings a "relief" of the open lake, but at the same time a shift of sedimentation into the reed belt.

The extent to which the load shift into the reed belt could be increased cannot be estimated with certainty for the entire lake, but the Manning-Strickler model of the flow rate for channels of different widths provides an indication (Figure 36). It shows that, in addition to the number and location of the channels, the width has a significant influence on the flow rate. This could also be clearly demonstrated in the hydraulic modelling (see Report 1 "Hydrology" of the Austrian researchers), even if concrete data on water and mass transfer in channels of different widths are not available. (Questions concerning the different approaches to channel construction and restoration in Hungary and Austria – see Figure 37 – are addressed in the Management Plan).

Based on the above-mentioned models we can estimate that a doubling of the net suspended matter loads in the reed beds is realistic. Furthermore, on the discharge side a

[1] In both cases, however, it should be added that "current" means the situation at the time of the field surveys (autumn 2017 to spring 2019, in the Illmitz area until autumn 2019). In some channels a very fast reed growth could be observed, even in the comparatively 'busy' channel to the Biological Station Illmitz. It is quite possible that the channels used in the project will lose their continuity within a few years, which would mean that the status quo would move towards scenario S1.

[2] An interesting question in this context is whether an increased retention area is also relevant from the point of view of flood protection of nearshore infrastructures in case of strong wind-induced transport of water masses. This cannot be answered with certainty at present but seems worth a separate investigation.

lower “need” for dredging in marinas is possible, but more frequent restoration of reed channels would be necessary to maintain the scenario S2 as such.

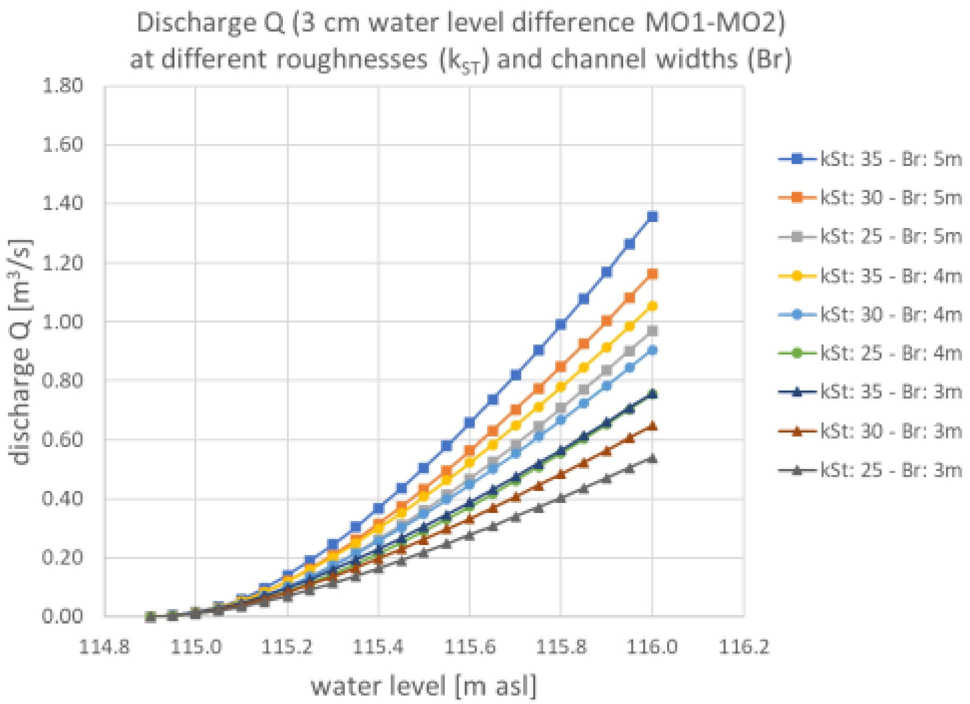


Figure 36. Relation between water level and discharge through a channel near Mörbisch assuming varying channel width, using the Manning-Strickler model (MO1 lake edge, MO2 reed belt).

Figure 37. Reed channels with varying width. Bottom left: near Fertőrákos in 2015 (Hungary), bottom right: near Mörbisch (Austria). Photos: R. Kovács (bottom left), G. Kum / DWS Hydro-Ökologie (bottom right).

The reconstruction of the reed channels in 2015 was the most visible management measure of the last decade in the Hungarian part of Lake Neusiedl / Fertő and can lead to important insight into what to expect from scenario S2. According to the hydrodynamic study (Report 1 by the Hungarian researchers), channels succeed in improving hydraulic connectivity within the Hungarian reed belt, but this does not come with unambiguously positive consequences. At medium lake water levels, channels act asymmetrically due to the lake dam: they do not enhance wind-induced flooding significantly, but they help drain the reed belt at the end of the flooding (or at the start of a wind setdown), reducing water retention of the reed bed. Also, the downside of flushing brown-water from the reed is that more organic matter ends up in the lake, where decomposition processes draw oxygen.

To demonstrate the effect attributable to the reconstruction of the Hungarian reed channels, we simulated pre-reconstruction conditions by assigning a hydraulic conveyance equivalent to the earlier geometry but using the present (reconstructed) geometry. Results indicate that reconstructing the reed canals amplified the fluctuation of the water surface (measured by the standard deviation of the water level) in the innermost portions of the canals by a few 10% (Figure 38) in the case of low lake water. As a response, however, the duration of water cover in the reed stands has not increased significantly (Figure 38). However, the flow rates, *i.e.*, the flushing effectiveness was increased up to 10-fold in some channels thanks to the reconstruction. This translates into a 3-fold increase in current velocity and a much deeper influence of the open lake into the reed belt, again at low lake levels.

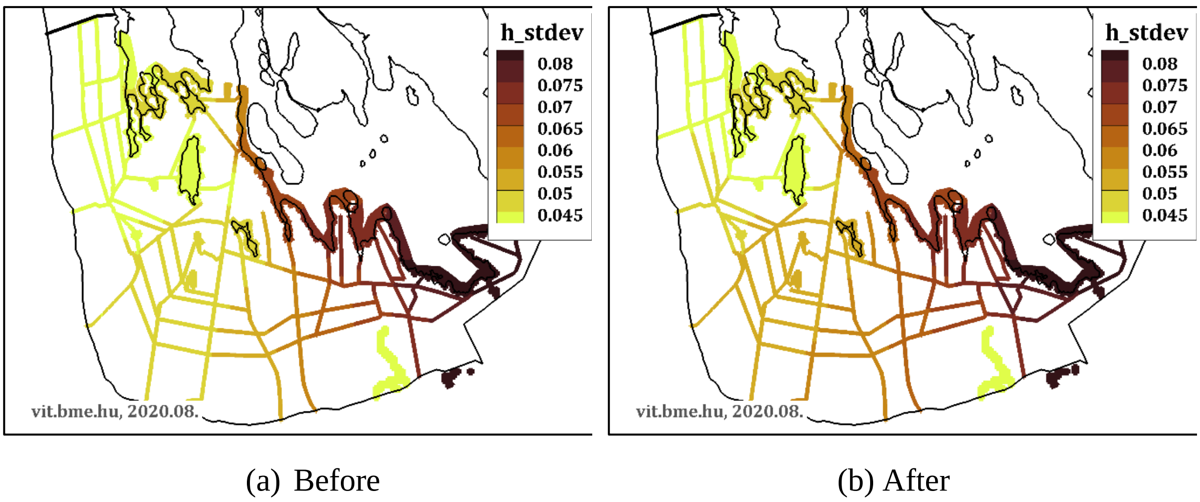


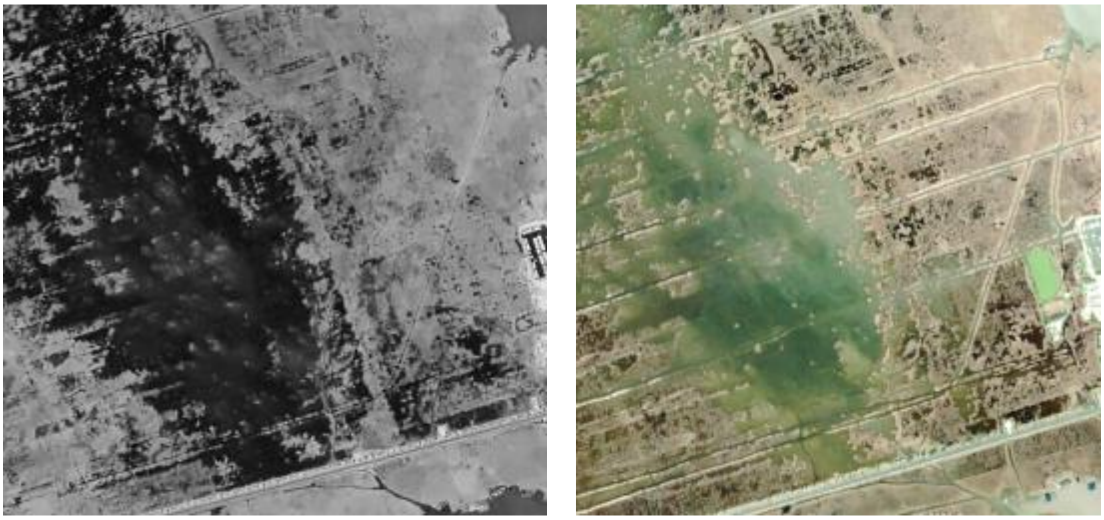
Figure 38. Standard deviation of wind induced water level fluctuations in the channels (a) before the reconstruction and (b) at present, modelled for low water level (115.30 m asl), in [m].

Based on these results and the parallel "ATHU2 Vogelwarte -Madárvárta 2" project, it can be concluded that the reconstruction has had no significant effect on the water regime and ecological state of reed stands at low water level as in 2019. According to the studied physical, chemical and biological factors in the "ATHU2 Vogelwarte -Madárvárta 2" project, it was assessed that water exchange in the water system of open lake – channel - reedbed can be detected at a distance of 1 km into the reed belt, on average, with a maximum of 1.5 km at relatively low water levels of the survey period (2017–2019). Whether the absence of any clear improvement of reed quality is due to the rather low water levels, to a not sufficiently high impact of the channels on water exchange, or to other causes could not be determined from the data collected in this short period.

The sharpest spatial pattern was presented by coloured dissolved organic matter (CDOM) in South-West, closed and decaying reed sites (periphery area of Fertőboz and Sopron), as well as in reconstructed channels located there, implying that despite reconstructing the channels few years earlier water exchange between the open water and these sites did not happen.

During the reconstruction of the Hungarian channels the dredged material was deposited alongside the channels and cut through at every 80 metres or so, with a width of 4 m. For surface flow, the interface length between the channels and the reed stands were therefore reduced to 5% as compared to earlier. Areas disconnected from water supply have to be restored depending on the long-term objective. It seems there are two possibilities: retain and restore the reed or restore the open water habitat.

A key question in scenario S2 is how long sediment discharge into the reed belt will be possible. So, it is not a question of *whether* the reed belt will eventually fill up with sediment, but only *by when*. A comparison of different orthophoto images from the reed belt gives an indication. Figure 39 shows a section of the reed belt at Mörbisch from the 1990s (before the channels were rehabilitated) as well as from spring 2012 and 2020. The comparison does not show any significant change in the reed beds in the open water area of the reed belt. If the colours of the Google Earth images are reliable, the grey areas in the reed water area in 2012 indicate a noticeable input of suspended matter and fine sediments in this area (in the eastern part of the water area near the channels to the open lake). This seems to be even clearer in the satellite image from 2020 (lake turbidity in the northern part of the open water area).



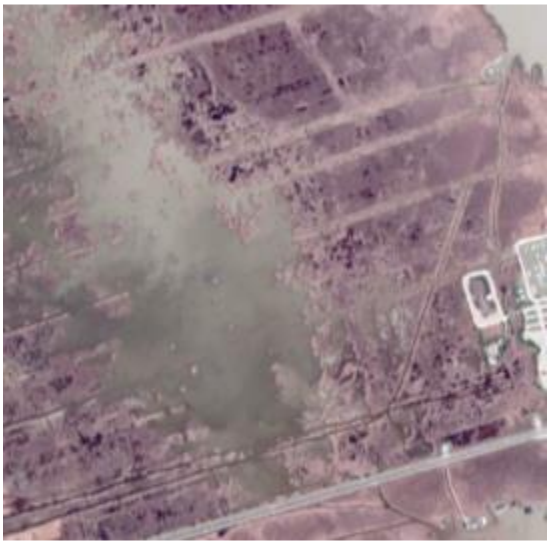


Figure 39. Comparison of the reed belt near Mörbisch in the 1990s (top left), in spring 2012 (top right) and 2020 (bottom left). Source: 1990s Biological Station Illmitz, 2012 & 2020: Google Earth.

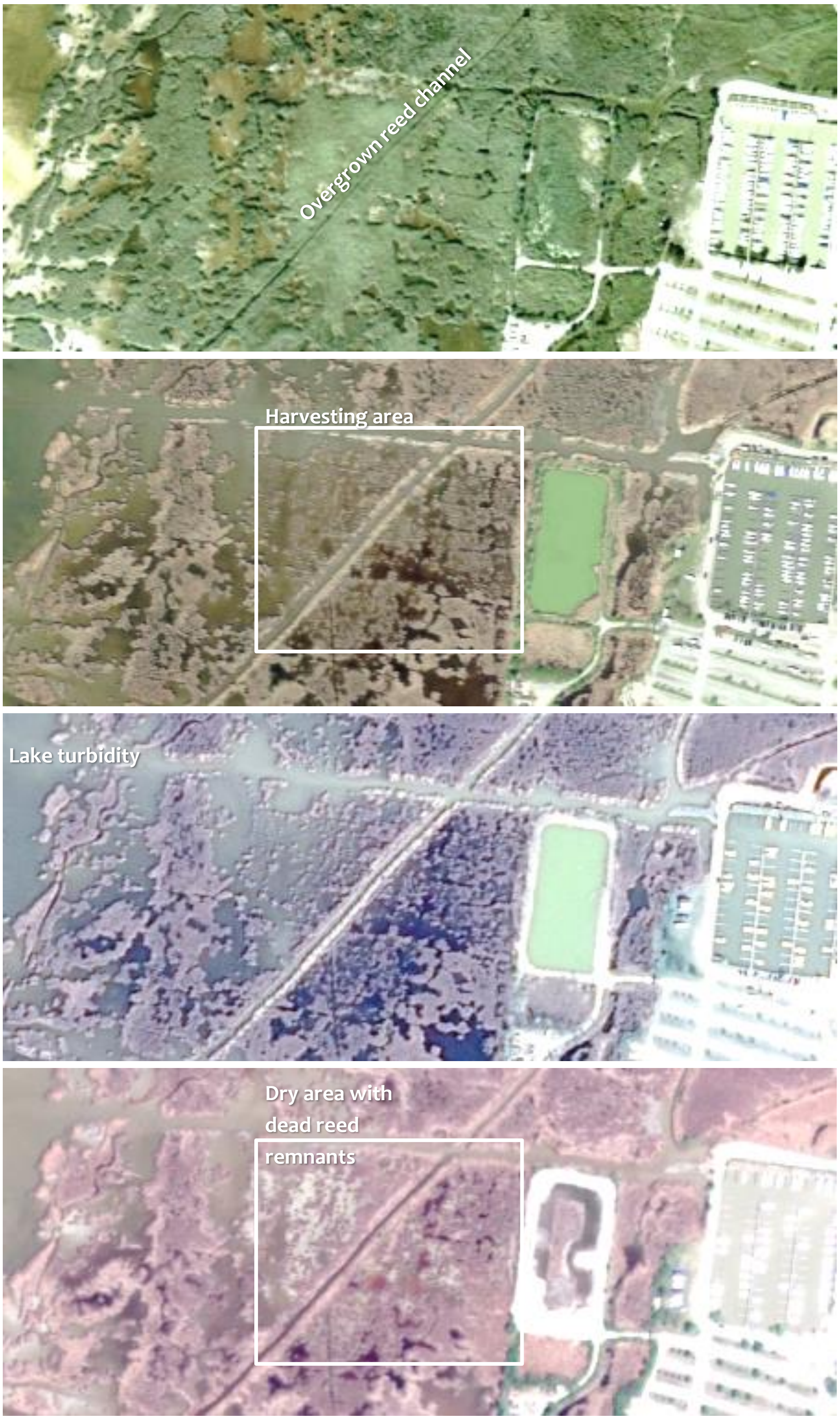
Of course, this comparison is very rough and can only give clues. A detailed photogrammetric analysis would certainly be necessary for reliable quantitative statements. Nevertheless, the figures show that the siltation process is also progressing noticeably within one to two decades. With decreasing retention space in the inner reed belt, however, a decrease in the inflowing water and suspended matter loads can be expected. The process would therefore slow down with regard to the input of solids from the open lake – which would mean that sedimentation would again increasingly occur in sheltered areas of the open lake.

For clarification, it should be emphasized here that we are talking exclusively about sedimentation in the true sense, that means by (mainly inorganic) suspended solids. Effects on reed growth, *i.e.*, the amount of organic matter produced and contributing to sedimentation, are excluded here. This is especially true for the effects of the input of suspended matter and nutrients as well as related processes (*e.g.*, redox) on the physiology of the reed plant, *i.e.,* when and where it comes to an increase in growth or the death of reed beds. Whenever in this report we talk about sedimentation, this term refers only to elevations of the sediment (be it in the open lake or in the reed belt, possibly also as dams along channels). The growth of reeds and the production of living or dead organic matter (stalks, leaves, rhizome) – in short: sedimentation in the sense of a “reed formation” of the lake – are not discussed here. In this sense, questions about the effects of reed harvesting go beyond the scope of the REBEN project (see Chapter 2.5).

However, there is no doubt that these can have a significant influence on the exchange of substances by changing the potential retention space and creating new pathways through the reed. Also on this point, possible changes shall only be indicated by satellite photos (Google Earth). Near the sedimentary basin, which was built as an intermediate storage area during the dredging of the marina of Mörbisch, an area with very dense reed beds existed about 20 years ago. After a harvest in this area (before 2012; recognizable by very regular cut structures) the reed obviously could not recover here. Today the area presents itself as a sparsely passed water surface and thus as a potential sedimentation area, which obviously was not before reed cutting. However, according to the satellite image, the area may dry out earlier at decreasing water levels than it was the case before the reed cutting.

For phosphorus, analogous to the previously discussed scenario, an opposite development is to be expected, *i.e.,* an increased input of particle-bound phosphorus into the reed belt. By maintaining the channels and the deposition of sediment along the channels (according to current practice) a permanent removal of nutrients from the system occurs. However, a release of phosphorus in dissolved form from the sediments deposited in the open water areas within the reed belt is absolutely possible (see Austrian Reports 3 and 5) and is also to be expected. Ultimately, however, exports from the open lake to the reed belt and there into the sediment should clearly predominate, as is currently the case (see Table 6).

For this scenario, too, it is true that if effects on the water balance are neglected, an increased concentration of pollutants would have no negative effects on the open lake. In contrast to scenario S1, the discharge of particulate pollutants from the lake into the reed belt would be enhanced and therefore a tendency to reduce the risk of exceeding the limits for critical pollutants can be expected. In addition, however, as in scenario W2, the risk of remobilization of pollutants resulting from larger dredging measures for channel rehabilitation would have to be taken into account. Excavation and relocation of large amounts of sediment has the potential to promote the mobilization of pollutants from the sediment and thus to cause an increase of the concentration of dissolved pollutants in the open lake. Although no statement can be made at the moment about the quantitative extent of such an internal back load, in case of extensive dredging measures appropriate monitoring measures would be required.



before 2001

28th Apr 2012

2nd Apr 2017

26th Apr 2020

Figure 40. Changes of the structure of the reed belt in a small area near Mörbisch resulting from reed harvesting (source: Google Earth).

Finally, the extended network of reed channels is to be considered with regard to aquatic communities. These would undoubtedly benefit from an increased interconnection of the open lake and reed belt, as this would increase habitat availability and accessibility in the lake and expand the range of ecological niches. Assuming that the expanded channel network only affects the lake outside the national park, then S2 scenario also provides areas in the reed belt that are not connected to the lake. Species that prefer the separated areas in the inner reed belt (or are more competitive than the "open lake species" under the prevailing extreme conditions) were thus preserved in Lake Neusiedl / Fertő.

Finally, the considerations are presented in Figure 41, again with regard to effects on the overall balance for solids and phosphorus.

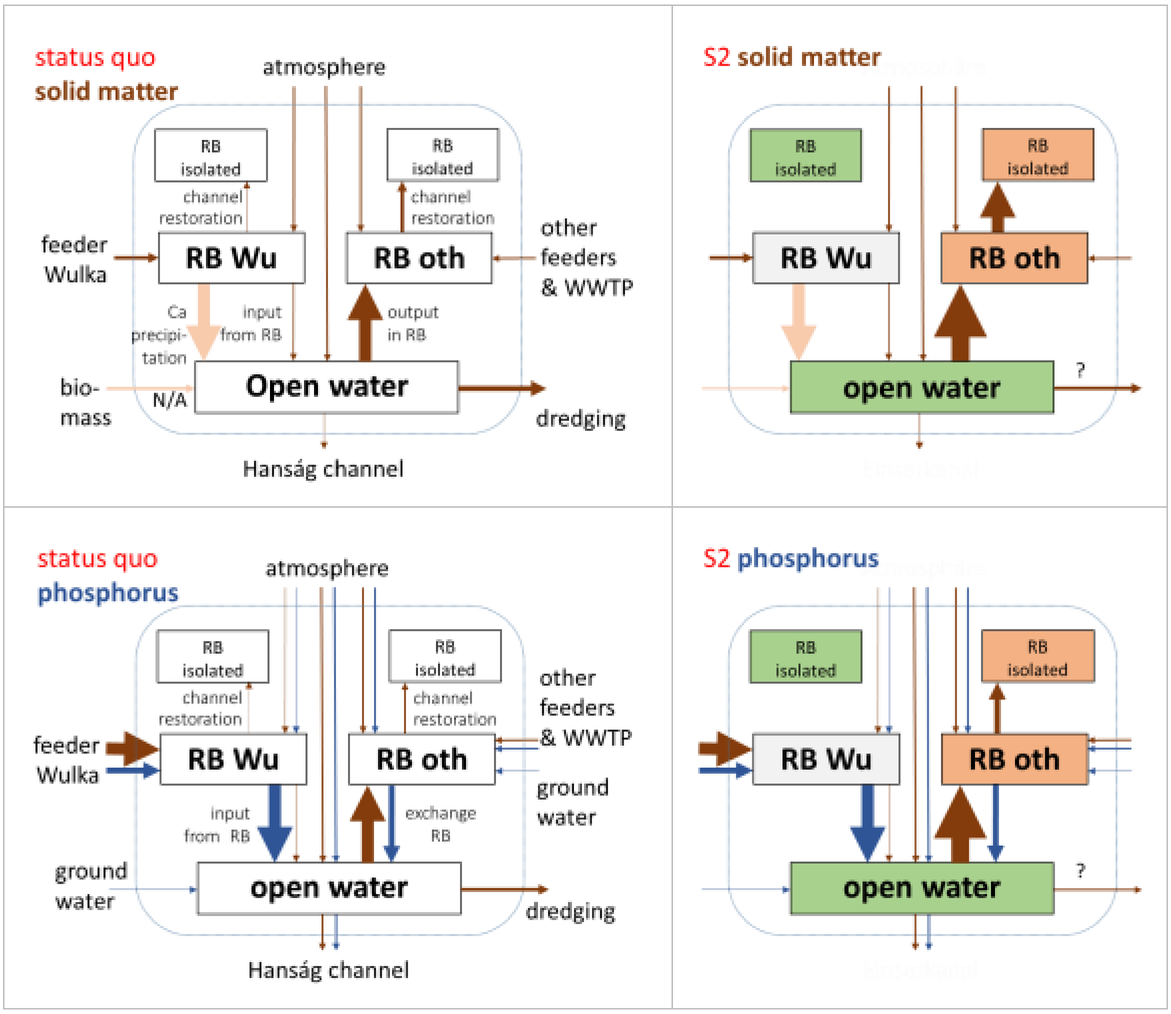


Figure 41. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario S2.

4.8 Résumé

The six scenarios presented are theoretical models that are intended to show trends and possible effects on the overall balances of solids, nutrients, and pollutants. The following conclusions can be drawn:

i) A **positive overall balance**, *i.e.,* an increase in solids, phosphorus and pollutants remaining in the open lake, is expected with a decrease in discharges from the lake (scenario P1 low water level) and dredging of channels (S1) (decoupling from the system by deposition on dams along the channels, mostly above 116 m asl). Conversely, increased discharges and dredging will lead to a decrease of the substances remaining in the open lake. This finding is not surprising, but the quantification in this report has shown that these changes are significant for the overall balance.

ii) For the **Wulka** Estuary area, the frequent dredging of the channel in scenario W2 would result in a continuous removal of substances. However, the retention of solids and pollutants in this area would be significantly reduced and the pollution of the lake increased. If the constant retention of substances in the Wulka reed belt remains by maintaining an at least partial diffuse flow, the long-term development of the deposition remains unclear. On the long run, removal of sediments from the reed belt would be necessary, which, however, is probably not a real option for financial and technical reasons. This leads to the question of the retention of suspended matter before entering the reed belt – an aspect that will not be discussed in detail here; for further discussion see Management Plan.

iii) In the **open lake**, fewer (or no) discharges at low water levels (scenario P1), a predominantly linear flow through the reed bed by the Wulka (W2) and the sedimentation of the reed channels (S1) cause an increase in the sediment load. The result would be an increased sedimentation in calm bays – possibly followed by more frequent activities to dredge material from marinas or bathing areas. A reverse development would be expected with a high water level and a broad network of reed channels.

iv) Lower discharges at low water level (P1) also lead to an increased **concentrating effect** of the lake. Thus, an overall increase in the concentrations of pollutants and phosphorus in the open lake (together with the processes described under iii) is to be expected.

v) The scenarios for the **reed belt** can be seen as a mirror of the development in the open lake. Thus, sedimentation with high water levels and sufficient water exchange via channels shifts clearly into the reed belt. This also increases the importance of the reed belt as a retention area or possible source of phosphorus and pollutants in the lake.

vi) In all scenarios the **water exchange** between lake and reed belt plays a central role. In a nutshell, these two compartments of the lake push the sediment and nutrient loads towards each other, depending on the general conditions. A real change in the overall balance is only given in case of discharges via the Hanság Channel and by dredging of the marinas. The deposition in the reed belt (reed channel dredging) removes solids, phosphorus and pollutants from the system involved in the exchange processes, but these ultimately remain within the boundaries of the basin of Lake Neusiedl / Fertő.

As explained above, the six scenarios basically consist of three opposing pairs. In combination, these scenarios can lead to an increase of decline of trends. For example, "P1W2S1" would correspond to a scenario with a largely linear flow through the Wulka reed belt and inconsiderable water and material exchange between lake and reed belt. The tendency to silt up in the open lake would thus noticeably increase. However, it is also possible that scenario S1 (reduced exchange between lake and reed belt, less flow of water to the littoral zone, no regular formation of large, shallow, and potentially easily warmed-up water surfaces) would reduce evaporation and thus promote scenario P2 (high water level).

If the focus of these considerations is mainly on solids, this is not least due to the fact that the mechanistic approach to the distribution and deposition of suspended solids appears to be relatively well established, both by measured data and by modelling. For nutrients and pollutants, the conditions are more complicated due to the conversion processes in the sediment. Nevertheless, it can be stated that for these substances, too, the temporarily predominant particulate binding is of decisive importance with regard to inlets and outlets and internal lake transport. On the basis of the findings of the REBEN project, it seems all the more urgent to take into account not only the inputs from the catchment area but also the lake-internal processes in all future water management considerations regarding sedimentation or water quality.

The six described scenarios represent models to illustrate the effects of different framework conditions on the mass transfer processes in Lake Neusiedl / Fertő. They were not defined on the basis of the expected development of Lake Neusiedl / Fertő in the coming years. But exactly this question is of course of great interest with regard to the management plan. First of all, it has to be clarified how the lake will develop in the next 20 years without human intervention.

This inevitably leads to a thematic field that has been addressed in Report 1 "Hydrology" of the Austrian expert team as well as further above in Chapter 2.5: the effects of **global warming** on Lake Neusiedl / Fertő. However, there are great uncertainties on this topic. In case of an increase of dry phases, the probability of scenario P1 (more frequent water levels

<115.2 m asl) increases, at least without human intervention. In addition, without regular maintenance of the reed channels, the lake will develop towards scenarios W1 (predominantly diffuse flow through the reed belt by the Wulka) and S1 (decoupling of the reed belt from the open lake). The scenarios W2 (linear flow) and S2 (extended channel network in the reed belt) are not feasible without ongoing interventions in the reed belt. A higher water level (Scenario P2) is possible both naturally (increased precipitation or reduced evaporation) and through changes in the existing water level regulation or an external water supply.

5 ASSESSMENT

This chapter summarizes the results of the scenario description and compares them with the most important water management objectives defined in Chapter 1.3 according to the Strategy Study Lake Neusiedl / Fertő (Wolfram *et al.* 2014).

In Chapter 3.7 it was emphasized that a clear delimitation of terms is important to allow evaluating the scenarios. Since the term "ratio of open water versus reed" occurs twice in the objectives of the Strategy Study Lake Neusiedl / Fertő, the following limitation and clarification is necessary: The REBEN project focuses on the dynamics of solids (suspended matter, sediment) and the dynamics of nutrients and pollutants (dissolved and particle bound). Aspects of reed growth and the problem of an increase of reed beds in the open lake were only marginally touched upon in the project and must therefore remain largely open in the evaluation.

For a clearer delimitation, the first objective in field of hydro-morphology according to the Strategic Study Lake Neusiedl / Fertő ("Preservation of the hydro-morphological characteristics of the lake basin in the open lake and in the reed areas (landscape element)") is also limited to sedimentation in the narrower sense (see above Figure 23 right). Likewise, the target "prevention of uncontrolled sedimentation of the reed belt (ratio of open water versus reed)" is considered exclusively from the point of view of sediment dynamics.

In the field "Reeds", too, the objective of the Strategy Study Lake Neusiedl / Fertő was formulated to maintain the ratio "open water : reed" and thus to counteract a progressive extension of reed beds on the cost of open water areas. This is specified here in such a way that the proportion of water areas within the reed belt (as well as the lake area as such) should be preserved (see Figure 23 middle).

In the following, the six scenarios are evaluated according to the objectives as defined in the Strategy Study Lake Neusiedl / Fertő. In a first step, the **current status** of all objectives according to the strategy study is evaluated in the text. In the **assessment of the scenarios** in a second step, the tendency to achieve the objectives or increase the risk of failing them is evaluated separately for each objective, then summarized in Table 7.

In a third step, it must finally be discussed if measures can be taken in order to **approach the objectives** faster. These include the measures already discussed regarding reed channels and water level, or by measures going beyond that, in the catchment area or in the lake itself. These points are discussed in a **separate document** and recommendations are made in the **management plan**.

The first water management objective, namely the preservation of the **hydro-morphological characteristics** of the lake basin in the open lake and in the reed beds (landscape element), describes on the one hand the status quo as such. On the other hand, it also includes the effort to maintain this state in the long term, *i.e.*, to **prevent the lake basin** (lake and reed beds) **from silting up**. However, sedimentation is a natural process, which cannot be prohibited in neither of the six scenarios. In this sense, the objective can currently be regarded as not achieved, and the six scenarios with changed conditions do not represent an approximation to the objective either. For a sustainable reduction of the suspended matter load from the Wulka, measures in the catchment area (partly also in the lake basin itself) are necessary *(strong evidence)*, which are dealt with in the management plan.

Even the goal of preventing the reed belt from silting up within the lake basin has not been achieved at present, as sediments are constantly being transported from the open lake into the reed belt. The prevention of the sedimentation of the open lake is not explicitly addressed by any of the water management objectives in the Strategy Study Lake Neusiedl / Fertő, but it seems to be reasonable to include this point in the list of goals – although even after the GeNeSee project it cannot be said with confidence whether this goal can be achieved at all.

Both objectives aim at the overall goal of preventing the siltation of the lake basin. Among the scenarios discussed, the sedimentation of the reed belt – in the sense of a restricted or prevented sediment transport from the open lake – can be ensured with P1 (low water level) and S1 (no channels) rather than with high water level (P2) and close interlinking of open lake and reed belt (P2). In the scenarios P1 and S1 at least no increase of the sediment layer in the reed belt is given by export from the open lake. In return, however, the sedimentation in the open lake will increase. The effects of the scenarios W1 and W2 are probably only marginally relevant for the reed belt as a whole, since only a small proportion is affected with the estuary area. The effects on the open lake, however, are more far-reaching *(strong evidence)*.

In the status quo, effective **exchange between the open lake and the reed belt** is only limited but would be much more pronounced in the scenario with high water levels (P2) than in the scenario with low water levels (P1). Since diffuse flow plays a negligible role, a broad system of reed channels is needed to enable lateral water exchange (S2) (*strong evidence*). The recently dredged network of channels in the Hungarian part, connected at both ends to the open lake, can provide a mean flow across the reed belt, providing fresher water to the reed but at the same time flushing organic matter into the lake, from low to high lake water levels.

Figure 42. Infiltration of the brown water into the open lake on 15th June 2019 (S2-image).

An assessment of the objectives in the field "Reeds" is difficult, not only because this field was only marginally included in the work program of the REBEN project, but also because the objectives in the Strategy Study Lake Neusiedl / Fertő are quite general. Without doubt, the reed belt today represents a unique landscape element with a high diversity of reed and brown water areas and is an integral part of the Lake Neusiedl / Fertő ecosystem. In this sense the water management objectives related to the field "Reeds" can be considered as achieved. At the same time, however, it implies the task of preserving this unique habitat in the future.

With regard to the scenarios, it can be assumed that falling dry of the reed belt over long periods (P1) is not compliant with the objective of preserving its uniqueness. This also applies to the current practice of channel dredging, which is decreased by the interconnection within the reed belt due to the accumulation of lateral dams (S2, W2). The long-term (vegetation-ecological) development of a long-lasting dry reed belt is unclear. However, a reed belt that has been predominantly dry for a long time is unlikely to be comparable with the diverse habitat that this part of Lake Neusiedl / Fertő represents today – despite the fact that even a predominantly dry reed belt in the broadest sense would still form an "integral part of the Lake Neusiedl / Fertő ecosystem" for a long time (*weak evidence*).

Further objectives address the **natural development** of Lake Neusiedl / Fertő. Strictly speaking, the lake today is not at all a natural system, but rather an anthropogenically strongly modified system: in hydrological (Hanság Channel), nutrient (eutrophication phase of the 1970s and 1980s) and structural terms (extension of the reed belt in the 20th century, construction and improvement of reed canals, dredging at the lake shore). In parts, the lake can develop undisturbed today, but only within the limits set by man for over 100 years and under the burden of impacts of past decades. The objectives for natural development can be understood to mean that the processes currently underway should be preserved or even (spatially or temporally) extended. This is already happening in the protected zone of the national park "Neusiedler See – Seewinkel". However, it may also be necessary to stop negative developments resulting from the long history of human impact in the ecosystem. Sustainable management can contribute to this, while leaving the lake to its own devices would be counterproductive.

In summary, it can be said that the objectives for **natural development** (chemism, dynamics, variability, processes) have been partially achieved today, but that in some cases impacts continue to counteract this. A scenario without the need for outflow via the Hanság Channel (P1) supports the objective for natural development. In scenario P2 with permanently high water levels, the risk of water export leads to negative ecological developments – with existing weir operation regulations. For this reason, especially in scenario P2, *i.e.,* ultimately when the currently endorheic lake is transformed into a "flow-through" water body, it is hardly possible to speak of an **undisturbed flow of biological processes** *(strong evidence)*.

The assessment of the scenarios with different cross-linking of open lake and reed belt is more difficult. Even if a complete decoupling of the reed belt from the open lake with the omission of channel dredging (scenario S2) can be regarded as a natural development, certain biological processes are inhibited or at least disturbed. In a system that is no longer completely close to nature such as Lake Neusiedl / Fertő, it therefore seems justified (or maybe even necessary) to support these processes by moderate measures such as maintaining a certain degree of exchange, but also migration paths between lake and reed belt. Even with such measures, the current processes can continue naturally and undisturbed in many areas (depending, of course, on the extent and nature of the interventions). With regard to the objective "preservation of natural variability", the assessment of the scenarios S1 and S2 is therefore ambivalent. The corresponding measures will therefore have to be specified in the management plan.

The achievement or **maintenance of good chemical status** (including the **chemical parameters** that are included in the assessment of **ecological status**) is currently not assured *(strong evidence)*. For a sustainable reduction of pollutant inputs, measures in the catchment area of the lake are to be considered (management plan). An increase in the effect of the concentration by the lake (P1), but also the elimination of the exchange (P1, S1) between the open lake and the reed belt means a deterioration or an increase in the risk of failing to achieve good status *(medium evidence)*. On the other hand, a mirror-image evaluation is given in case of high water levels and continuous restoration of the channels: Water constituents are diluted or the discharge from the open lake into the reed belt and the storage there by means of an internal back load from the reed belt prevails. The risk of a missed target becomes smaller *(medium evidence)*. Possible loads from the reed belt in the course of channel rehabilitation should be kept in mind to avoid a critical mobilization of substances *(strong evidence)*. A low trophic level and compliance with the EQS for nutrients is also facilitated when the water level is high and the channels are regularly maintained *(strong evidence)*.

For the **input of low nutrient loads**: If the lake is seen as a combination of reed belt and open lake, scenario W2 with a largely linear flow through the reed belt by the Wulka reduces the **external** loads in so far as this scenario is only possible with ongoing dredging. This implies the removal of sediment and nutrients before they can reach the open lake. In this sense, scenario W2 reduces the nutrient input into the lake – or correctly: the balance as a result of the dredging and extraction – to a certain extent *(weak evidence)*. The scenarios P1/P2 and S1/S2 have no influence on the external loads.

The **internal** nutrient loads are increased in scenario W2 with a purely linear flow through the reed belt since the deposition in the reed belt at the Wulka estuary is eliminated. If one interprets the goal of reducing the internal loads not only as reduced remobilization from the sediment, but also as increased and permanent deposition in the sediment, mainly by export into the reed belt, the scenarios P2, but also W1 and S2 promote this objective, the counter scenarios oppose it. The question of the possible effects of lake-internal measures (*e.g.*, dredging) on nutrient and pollutant remobilization directly as a result of the intervention in the sediment is open.

The following Table 6 summarizes the assessment. It is to be stressed again that this assessment considers the different basic conditions, which were defined with the six scenarios. The aim of the water management plan shall be to work out measures in order to find optimum achievement of the objectives, considering the contradictory or opposing processes involved.

Table 6. Assessment of the status quo and the selected scenarios against the water management goals according to the strategy study. Specifications and supplements to the objectives as defined in the strategy study are written in italics. The degree of approach to or distance from the objectives is indicated by – – to + +.

Field	Water management goals	P1	P2	W1	W2	S1	S2
Hydro-morphology	Preservation of the hydro-morphological characteristics of the lake *(no silting-up of the whole lake basin, i.e., lake and reed belt)*	–	–	–	–	–	–
	No silting-up of the reed belt *(minimized sedimentation of the reed belt)*	++	– –	–	+	++	– –
	No silting-up of the open lake	– –	++	=	– –	– –	++
	Enabling exchange lake – reed belt	– –	++	na	na	– –	++
Reed	Protection of the uniqueness of the reed belt, sustainable management (landscape element)	–?	+	+	–	+	–
	Preservation of the diversity, restriction of reed growth (open water *vs* reed)	–?	+	na	na	–	+
	Preservation of the reed belt as an integral part of the Lake Neusiedl / Fertő ecosystem	=	=	na	na	=	=
Phys.-chem. Parameters	Preservation of natural chemistry	++	– –	=	=	=	=
	Preservation of natural physical-chemical dynamics	+	–	+	–	+	–
	Low trophic level	– –	++	+	–	– –	++
	Low *external* nutrient loads	na	na	–	+	na	na
	Low *internal* nutrient loads (remobilization from sediment)	– –	++	+	–	–	+
Pollutants	Preservation of good chemical status	– –	++	=	–	– –	++
	Preservation of good chemical status (chemical compounds)[3]	– –	++	=	–	– –	++
Biology	Preservation of good ecological status (biology)[4]	+	–	–	+	–	+
	Preservation of natural variability (biodiversity, abundance and productivity)	+	–	+	–	±	±
	Biological processes should run largely undisturbed	+	– –	+	–	±	±

[3] *sensu* Qualitätszielverordnung Chemie Oberflächengewässer (BGBl. II Nr. 96/2006 idgF)

[4] *sensu* Qualitätszielverordnung Ökologie Oberflächengewässer (BGBl. II Nr. 99/2010 idgF)

6 KNOWLEDGE DEFICITS AND OPEN QUESTIONS

In 2014, Wolfram *et al.* (2014) summarized the current state of knowledge in various specialist areas in the Strategy Study Lake Neusiedl / Fertő and, based on this, formulated a number of knowledge deficits. The improvement of this knowledge was included in the list of strategic goals for the region Lake Neusiedl / Fertő.

One of these knowledge deficits concerns the water and material exchange between the open lake and the reed belt – a complex of topics that was the focus of the REBEN project. On the basis of different methodical approaches, REBEN was able to clarify essential questions. The results of the field surveys, laboratory tests, data evaluation and modelling form the basis for the water management plan, which was prepared as a separate document in agreement between Austrian and Hungarian experts.

As with every scientific study, new questions arose in the course of the work on the REBEN project, and so the present synthesis concludes with a chapter on the knowledge deficits that have arisen anew from the data analyses and in numerous discussions among experts from both countries.

(1) Terrain model

One of the most important points surprisingly represents the surveying of the lake basin of Lake Neusiedl / Fertő. A review of the available data from the GeNeSee project revealed that the surveys in the reed belt were not extensive and detailed enough to provide a suitable data basis for the planned modelling. Today we do not know to what extent the reed belt has silted up since the last surveys in the 1980s and 1990s, especially how much the height of the lake dam has increased. Uncertainties regarding the height of the terrain in the dense reedbeds made the modelling considerably more difficult.

At least in the three test areas of Illmitz, Mörbisch and Wulka estuary, supplementary measurements of the water depth of selected channels and pools were carried out in the REBEN project (beyond the scope of work commissioned). In combination with a GIS layer of the edge between the open water of the lake and the reeds as well as of the open water areas in the reed belt (Csaplovics & Schmidt 2011a; Csaplovics & Schmidt 2011b), they allowed for creating a digital terrain model for these three areas which could be used for hydraulic modelling. A comprehensive **survey of the sediment levels** in the reed belt, especially in the area of the lake dam, but also on land, is considered by the authors as an essential task for the coming years. The information to be gained from this is also indispensable for considerations on a water supply to Lake Neusiedl / Fertő.

(2) Reed growth and reed dieback

The observations on sediment formation and mass transfer between lake and reed belt in the present synthesis report focused on the mineral components. However, the question of organic material production and its contribution to sedimentation is not sufficiently known. The last investigations on this topic date back several decades and undoubtedly need revision and supplementation. Connected with this are questions about reed growth, but also about reed dieback in the inner reed belt. Specifically, it should be clarified in which areas there is an **expansion** or a **decline of reed stands**.

After decades of cooperation a really standardized, homogenous reed survey and qualification for the whole lake is necessary.

(3) Impact of sediment dredging

The importance of sediment removal by dredging of marinas and of channel rehabilitation for the overall balance was discussed and evaluated in detail in this report. However, we do not know to what extent these sediment interventions lead to a **remobilization of nutrients and pollutants** in the open water and what short-term (but ultimately potentially longer-term) effects such remobilization has.

(4) Reed harvesting

The economic use of the reed belt through reed cutting directly affects the nutrient and solid matter balance of the lake. Again, this raises the question of **remobilization of nutrients and pollutants** that were previously deposited in the reed belt. In addition, however, the **quantities of substances** that are **removed** from the system during reed harvesting should also be reassessed. The last studies on this topic date back about 40 years.

(5) Compliance with environmental quality standards (EQS)

Austria

From biota investigations in Lake Neusiedl / Fertő it is known that the EQS for mercury and PBDE are not being met. This is not a specific feature of Lake Neusiedl / Fertő, as the target is not met throughout Austria and large parts of the EU. A monitoring of the parameters of the Qualitätszielverordnung Chemie Oberflächengewässer (QZV Chemie OG, Ordinance on the Chemical Standards in Surface Waters, BGBl. II Nr. 96/2006) in the water phase of the Lake Neusiedl / Fertő is missing so far, because the national monitoring program according to the Gewässerzustandsüberwachungsverordnung (GZÜV, Ordinance on Monitoring of Surface and Groundwater, BGBl. II Nr. 479/2006) does not include a monitoring point at the Lake Neusiedl / Fertő. The present investigations within the scope of this project were not designed for the monitoring of EQS. Nevertheless, the investigations indicate possible exceedances of EQS for PFOS, benzo(a)pyrenes, fluoranthene and other PAHs as well as dissolved lead. However, it is not possible to make a final statement on the current achievement of the target.

Hungary

In the second RBMP (2015), the Lake Neusiedl / Fertő classification of monitoring results:

Category of water body	Biological status	Physico-chemical status	Specific pollutants	Hydro-morphological status
natural	good	good	good	high

(6) Degradation and adsorption of pollutants

A number of substances that are largely persistent in the environment are removed from the aqueous phase in the lake and its reed beds to a relevant extent. In addition to a discharge with solids into the reed belt as well as a storage there (PAH and metals) and the associated questions of a long-term possible mobilization (see above), for other parameters this must be attributed to a degradation or conversion under the environmental conditions of the lake (*e.g.*, carbamazepine, diclofenac, PFOA). The end products of these degradation processes or a possible formation of metabolites have not been identified. Also for PFOS, a relevant removal from the aqueous phase in the lake could be shown, but the fate of PFOS could not be completely clarified. While PFOA and PFOS belong to the group of perfluorinated surfactants (PFT) whose use is declining, they are increasingly replaced by other mostly short-chain PFT. These are examples of extremely persistent chemicals, about whose input and behaviour in the lake there is currently little information available, and which must be viewed critically in the long term under the sensitive conditions of the lake.

(7) Benthic production

Despite promising results in previous studies (Wolfram *et al.* 2015), the planned sampling of the benthic communities in the present concept was methodologically uncertain and subject to errors. In agreement and with the consent of the client, the analyses of the algal benthos (phytobenthos) were therefore removed from the program and replaced by fish ecological investigations. However, especially in the shallow brown water areas in the inner reed belt, benthic production can be a relevant element of the biomass input into the system. Therefore, no statement could be made in the project about the subsequent consumer chain, the herbivorous and carnivorous bottom-dwelling animals (insect larvae, snails, mites etc.), which in turn are the food source for benthic fish.

(8) Microbiology and nitrogen cycle

The fate of organisms that have died in the water, of dissolved organic compounds and of organic substances supplied from outside are central questions of the limnic matter balance. In stagnant waters, almost all material incorporated in the organisms must ultimately return to the water and only a small proportion is fixed in the sediment. This return occurs mainly through microbial degradation, which can occur at different rates and in different stages. The questions of which bacteria are involved and to what extent the dissolved substances are reintegrated into the material cycle also play an important role in understanding the system processes. While REBEN has been able to provide extensive knowledge regarding the phosphorus balance, the far more complex nitrogen cycle, in which microorganisms intervene in many different ways, has hardly been investigated.

(9) Exchange with groundwater

The primary source of the high $Na–HCO_3–Cl$ content of soda lakes and pans in the Carpathian Basin is discharge from upwelling deep saline groundwater, which is enhanced by evaporation. This hydrogeological impact on the water balance and chemistry is still unknown in Lake Neusiedl / Fertő and should be investigated for the future more effective lake management.

(10) Lateral exchange along channels

A significant grey area in our knowledge of Lake Neusiedl / Fertő is the hydraulic connectivity between the channels and the adjacent reed. More specifically, the impact of the dredging deposits on surface flows and the effectiveness of the cuts along the Hungarian channels, as well as the conductivity of the substrate. To mitigate the challenge of surveying channels via remote sensing, field data (*e.g.*, tracer concentrations) should be collected in pilot areas of the dredged channels, covering low to high water regimes.

(11) Evaporation

There is still a high uncertainty around the actual evaporation rate of Lake Neusiedl / Fertő. Without more reliable estimates of evaporation, the uncertainty of any analysis on water balance remains high. Replacement of the formerly applied evaporation calculation method with the Penman equation is also suggested due to its proven success for Lake Balaton and Lake Velencei in Hungary.

(12) Continued monitoring

Further long-term monitoring of the open water-canal-reed water system is needed, in particular for key limnological factors and indicators in different hydrological and meteorological situations, in order to plan the appropriate lake management and restoration strategy. The impact of the channel reconstruction in the Hungarian reed belt could only be experienced at low to medium water level. Similarly, the hydrodynamic model of the reed belt can be considered validated only for lower water levels that prevailed during the survey. In addition to a continuous monitoring activity, we recommend conducting field survey missions at the occurrence of steady high water.

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