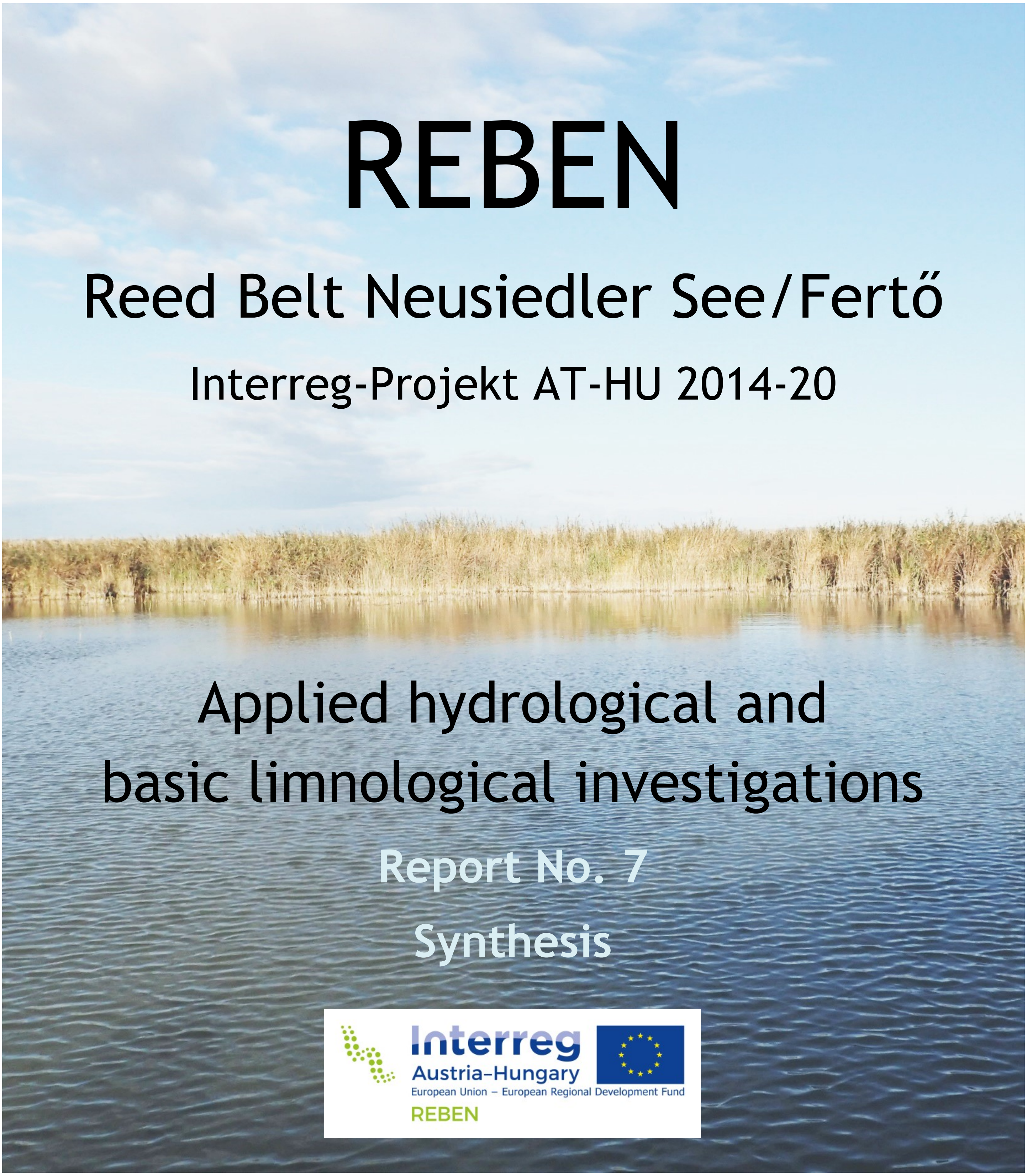
DWS Hydro-Ökologie



REBEN

Reed Belt Neusiedler See/Fertő

Interreg-Projekt AT-HU 2014-20

Applied hydrological and basic limnological investigations

Report No. 7

Synthesis

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REBEN

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EXECUTIVE SUMMARY

Objectives of the project REBEN

Lake Neusiedl is one of the largest and most important natural and cultural landscapes in Central Europe. From earlier studies it was known that a functioning water and material exchange between the open lake and the reed belt is of great importance for the preservation of a good water quality, but there were serious knowledge deficits about the processes and key factors behind.

The aim of the project REBEN was to close these knowledge deficits and thus create a basis for defining water management measures. The project is divided into two work packages. In work package T1, investigations in the fields of hydrology, chemistry and biology were conducted to improve our knowledge of the exchange processes between the open lake and the reed belt. Based on this, a bilaterally agreed water management plan will be developed in work package T2 (separate document).

The present synthesis provides a summarizing description of the results of the **work package T1** (investigations on hydrology, physico-chemical parameters and pollutants, reed structure and sediment), the evaluation of the status quo from hydrological, chemical, limnological and water management perspectives as well as the **assessment of alternative scenarios** under changed framework conditions. The evaluation 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 concern three key points:

- the risk of silting-up of the lake (and especially the reed belt),
- the protection of water quality (chemistry) and
- the maintenance of good ecological status (biotic communities).

Inputs from the catchment area

The once wide flow through of the river **Wulka** through the **reed belt** no longer exists to the same extent as before. This is probably due to the constant input of solids into the reed belt, which have been piled up along the **channels** during their **regular restoration**. This led to the formation of longitudinal dams, which only allow flow through a few openings. The results of the project REBEN confirm the importance of the **chemical and biological processes** in the reed belt as known from previous investigations. However, there were also clear differences: today the Wulka flows more rapidly and quasi **linearly** through channels towards the open lake, whereas in the 1980s a **diffuse** and slow flow through the reed belt was predominant, with more pronounced processes such as denitrification and phosphorus dissolution.

Spatial patterns and gradients

On a smaller scale, the reed belt presents itself as a **mosaic** of dense reed beds, young or old reed beds and open water areas. A wide band of dense reed and higher sediment cover is found almost all around the open lake, while the **large open areas** are characteristically found in the inner reed belt areas (especially at Mörbisch and Illmitz). The numerous artificial **reed channels** are breaks through this **lake wall** and at the same time the preferred transport paths from the lake to the inner reed belt areas. Along these linear structures run decreasing gradients of suspended matter, *i.e.* inorganic particles as well as plant and animal plankton. At the same time, the channels are also migration routes for fish.

An obvious **gradient** is the decrease of water depth from the lake towards the shore meadows. In areas that are not connected to the open lake at all or only via very long channel paths, the concentration of **dissolved solids** in the water in the reed belt can be three times as high as in the open lake. Small-scale structured reed beds are also characterized by temperature extremes and, due to massive degradation processes, by intensive oxygen consumption up to completely anoxic conditions. Similar gradients as in the water column characterize the physico-chemical composition of the **sediment**. For example, the organic content – and with it the content of various **pollutants** – as well as the water content increase significantly along the transects from lake to land. The following influencing factors and causes are responsible for the gradients found: the **water level** (depending on precipitation and inflows versus evaporation and discharges), the 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 – as well as the construction and restoration of **channels**, which function as priority transport pathways between the open lake and the central reed belt.

Exchange processes

Mass transfer takes place at **different levels**, namely between the open lake and the reed belt, between the different areas within the reed belt and between the sediment and the water column. These processes are 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 alternation between windless phases and those with a strong influence by wind and waves (seiche movements, *i.e*. standing waves comparable to a regular tilting of the entire lake water level).

At present, the **channels connected to open water areas behind them** are of the greatest importance for the exchange of water and substances between the open lake and the reed belt. The channels are the preferred transport routes for suspended matter (as well as nutrients and adsorbed 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 when the water level is high, a diffuse flow through the reed belt can occur to a small extent.

Adsorption tests have shown that for certain substances (*e.g.* PFOS) there is still a sufficiently high **adsorption capacity of the sediment** in the reed belt. For other pollutants (*e.g.* some heavy metals), however, the adsorption capacity is almost exhausted and thus there is a potential for re-solution or concentration increase. That this has not (yet) happened is probably due to the fact that new sediment (especially Ca-Mg-carbonates) is continuously generated and provides new adsorption surfaces.

Loads of solids, nutrients and pollutants

Most of the **solids** introduced into the lake from the Wulka remain in the reed belt of the estuary. The newly formed sediment in the lake (Ca-Mg-carbonates, so-called "lime mud" or Kalkschlamm) exceeds by far the solids load in the tributaries. In years with large amounts of lake water discharged via the Hanság Channel, a considerable load of turbidity and thus fine sediment is also discharged from the lake. Nevertheless, at present high suspended sediment loads are continuously being transported from the open lake into the reed belt and are thus a driving factor of potential sedimentation in these areas. Just like the regular dredging in the marinas and bathing areas, the restoration of channels also have a noticeable influence on the overall sediment balance of the lake. The dredging of sediment from the channels definitely removes solids from the lake, even if they remain within the boundaries of the lake basin. Lateral sedimentation in the form of longitudinal dams, however, has a lasting effect on the structure and character of the reed belt.

In contrast to the solids, a lower proportion of **nutrients** (phosphorus) is retained in the Wulka estuary, and the largest part reaches the open lake – albeit sometimes with a time lag. Nevertheless, on average over the last 20–25 years, about 3 tons of phosphorus per year from the Wulka catchment area remain in the reed belt, which thus represents an important retention area for nutrients. The discharge from the reed belt into the lake is primarily in the form of dissolved phosphorus and is lower than the lake's input into the reed belt, which is mainly in particulate form. Dredging is not as important for the nutrient balance as it is for the solid matter balance, but it does contribute to a significant removal of nutrients from the system.

Among the **pollutants**, PFOS (perfluorooctane sulfonic acid) and PFT (perflourized surfactants) are those substances that are discharged into the lake via deposition and are not found in the known discharges. Fluoranthene most probably settles in the reed belt, which however indicates a potential reloading of the lake from the reservoir in the reed belt – as it could be shown for phosphorus.

Long-term developments

In addition to short-term transformation and exchange processes, long-term developments are of importance for Lake Neusiedl. Although they have not been investigated in this project, they must be taken into account in the water management plan: on the one hand, the **natural sedimentation** of the system through continuous input of solids from the catchment area as well as the autochthonous sediment formation, on the other hand, **global warming** with already proven effects on the hydrology of the lake.

Scenarios – different framework conditions

Six scenarios were used to demonstrate the effects of different framework conditions on existing processes:

- Scenario P1 water level <115.2 m asl
- Scenario P2 water level >115.8 m asl
- Scenario W1 only diffuse flow of the Wulka river through the reed belt
- Scenario W2 only linear flow of the Wulka river through the reed belt
- Scenario S1 no channels or existing channels silted up or grown together
- Scenario S2 expansion of the existing network of channels

Based on the description of the scenarios, **effects on the overall balances** of solids, nutrients and pollutants can be derived. Decisive changes are to be expected above all when the reed belt is disconnected from the open lake at low water levels and overgrowth of the channels, especially in areas where the channels act as a connection between the open lake and extensive brown water areas in the reed belt (*e.g.* at Mörbisch). In some scenarios side effects have a great importance on the chemism and the material balance of the lake, *e.g.* in scenario W2 a continuously necessary dredging of the Wulka in the estuary area or in scenario P2 a frequent discharge of lake water and thus of salts from the lake via the Hanság Channel.

Assessment

The six scenarios were finally presented in an assessment matrix with regard to the water management goals according to the Strategy Study Lake Neusiedl. It did not result in a consistently positive or negative picture for any scenario (in the sense of approaching or moving away from the targets). This underlines the complexity of the different processes and leads to the management plan, which shall identify the measures to strengthen the positive developments and to avoid or at least mitigate negative trends.

Knowledge deficits and open questions

During the project, new questions arose, which are summarized below as priority knowledge deficits in keywords:

- Terrain model in the area of the reed belt
- Reed growth and reed die-back
- Short-term effects of sediment dredging on the release of nutrients and pollutants
- Effects of reed harvesting on the release of nutrients and pollutants
- Compliance with environmental quality standards (EQN) according to the EU Water Directive
- Degradation and adsorption of pollutants
- Benthic production in the reed belt
- Microbiological processes and nitrogen cycle

1 INTRODUCTION

1.1 Baseline situation

In 2014, strategic goals for the Lake Neusiedl 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. However, it underlines all the 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 the hydrological, chemical and ecological interrelationships is it possible to provide stakeholders and political decision-makers with the necessary certainty for decisions with potentially far-reaching consequences.

Compared to other waters in Central Europe, Lake Neusiedl 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 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 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. What we do know, however, is that the extensive littoral zone is of utmost importance for the water quality of the lake and thus is relevant for 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 were carried out during the 1980s (Brossmann *et al.* 1984). 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 – 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):

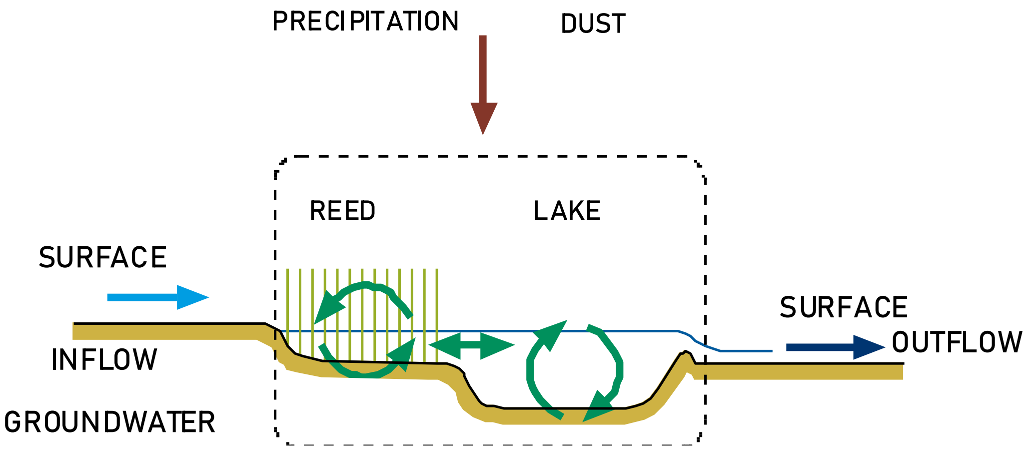


Figure 1. Scheme of inputs, outputs and internal processes in Lake Neusiedl. Source: Stalzer & Spatzierer (1987) (modified).

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 wall), and on the other hand for methodological reasons (*e.g.* individual sampling *versus* water quality measuring stations).

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 beyond the Wulka mouth (Mörbisch, Illmitz). A milestone above all the different approaches for modelling are 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, and the major findings will be summarized in a synthesis in the following 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

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 the open water and about the relevance of these processes for water quality should be improved.

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

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: Inclusion of 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

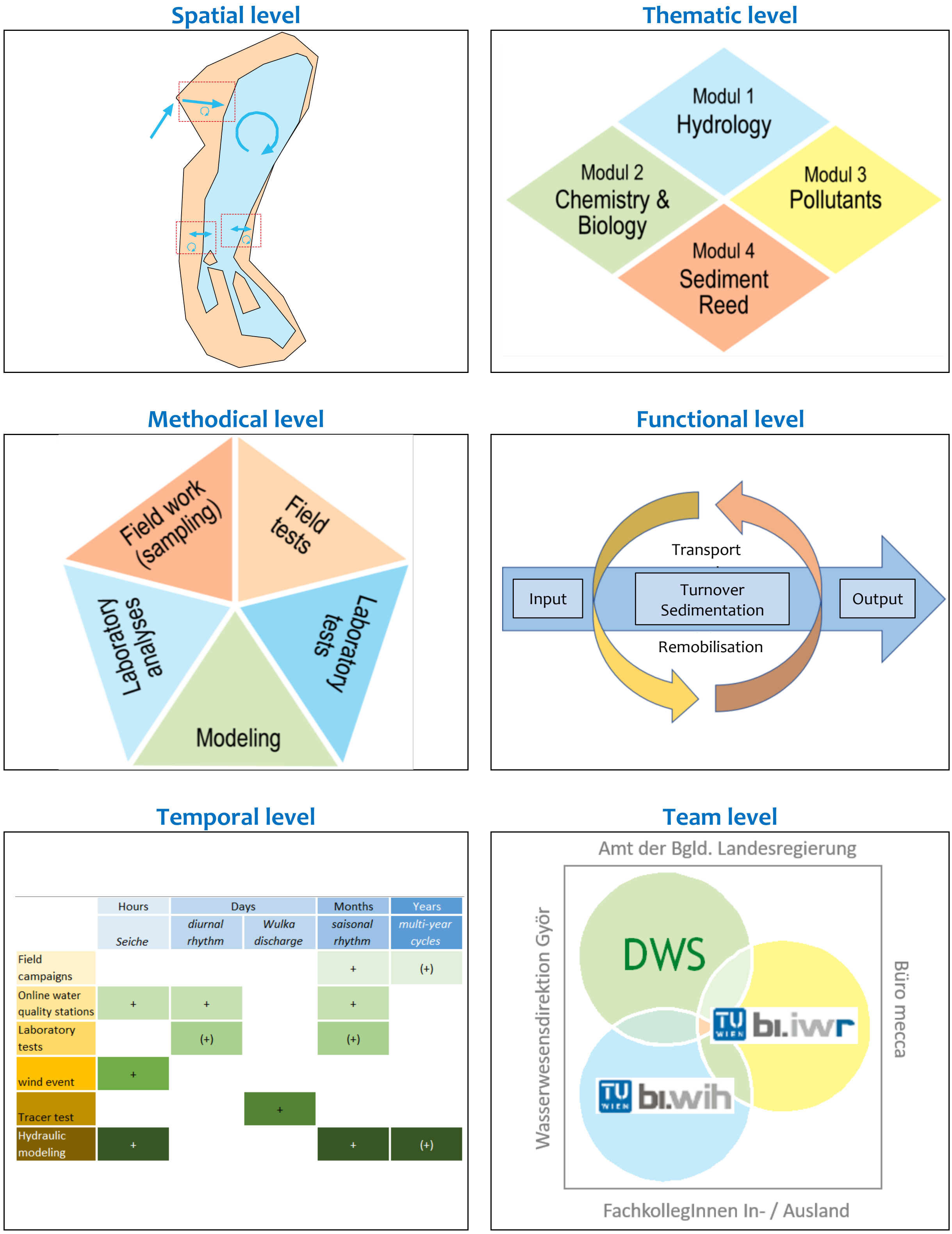
Reed/Sediment Investigation of sediment structure and composition depending on hydrological conditions at several dates

The results of the investigations of the four modules within the work package T1 (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 (as defined in the structure of WP T1) in the following sectoral reports:

Report 1	Hydraulic modelling
Report 2	Reed (Processing of GeNeSee data, uses of reed)
Report 3	General physico-chemical parameters in open water and sediment; pollutants (trace substances)
Report 4	Biology
Report 5	Online measurements (water quality monitoring stations) and field tests
Report 6	Laboratory tests

1.2.2 Approaches

The work packages were managed by a team of experts from DWS Hydro-Ökologie and two institutes of Vienna University of Technology. The approach covered several levels: spatio-temporal, thematic, methodological and functional (process level). The complexity of the task is schematically illustrated in Figure 2.



	Hours	Days		Months	Years
	Seiche	diurnal rhythm	Wulka discharge	saisonal rhythm	multi-year cycles
Field campaigns				+	(+)
Online water quality stations	+	+		+	
Laboratory tests		(+)		(+)	
wind event	+				
Tracer test			+		
Hydraulic modeling	+			+	(+)

Figure 2. Approaches to the work of the project REBEN on different levels.

1.3 Assessment benchmark

The **present synthesis** serves as:

- the summarizing **description of the results of 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 AP 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 evaluation criterion is of course of great importance here. 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 maintenance of good ecological status (biotic communities)

The aim of the synthesis is to achieve general statements for the whole lake, based on findings at local level (*i.e.* in the three test areas). Similarly, the management plan (work package T2) does not aim at measures with only 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 hydromorphological 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 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. 2 Matter transport, processes and loads
  - Chap. 2.1 Inputs from the catchment area
  - Chap. 2.2 Spatial patterns and gradients
  - Chap. 2.3 Exchange processes
  - Chap. 2.4 Mass balances
  - Chap. 2.5 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 MATTER TRANSPORT, PROCESSES AND LOADS

2.1 Inputs from the catchment area (Wulka)

- *Inputs into the river Wulka*

The Wulka is the largest tributary into Lake Neusiedl and – in addition to the atmospheric input and the wastewater treatment plants that discharge directly into the lake – 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, where heavy rain falls can wash off considerable loads of particle-bound nutrients into the Wulka. On the other hand, the northern Burgenland region is comparatively low in precipitation as compared to other regions in Austria; in dry seasons, the effluent 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).

Whereas the load of suspended solids in the Wulka originates almost exclusively from agricultural erosion, the phosphorus emission accounts – in a long-term average – to 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 the implementation of wastewater treatment with extensive phosphorus and nitrogen removal , wastewater effluents account for about 20–25% of the emissions into the Wulka for both nitrogen and phosphorus.

Trace substances and pollutants are also emitted into the Wulka via diffuse and point sources. Figure 3 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 perfluortensides 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.

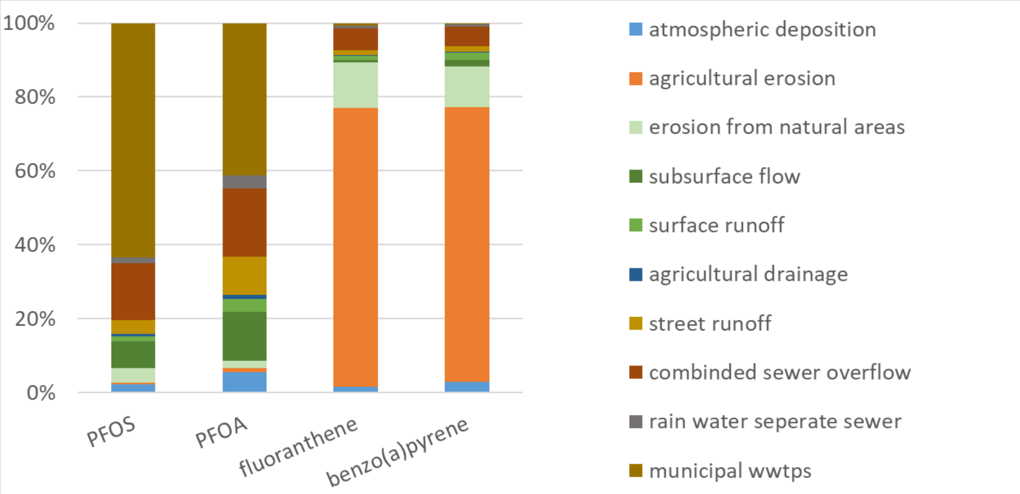


Figure 3. Emission pathways into the river Wulka (Zessner *et al.*, 2019).

Inputs from the Wulka into Lake Neusiedl

Before the Wulka actually flows into Lake Neusiedl, it flows through the several kilometres wide reed belt. As has long been known, this is where manifold and complex transformation processes take place. The fact that the findings of 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 channels sediments were deposited along the reed channels and thus longitudinal dams were created, which allow a flow through 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, it seems clear that today the linear flow predominates (Figure 4) (Wolfram *et al.* 2019).

Basically, the current investigations confirm the importance of the transformation processes in the reed belt. However, there are significant 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, since retention of particulate phosphorus and dissolution of dissolved phosphorus were in balance. Nitrogen concentrations have been reduced due to denitrification, but there is no evidence of complete depletion of nitrogen at to the mouth

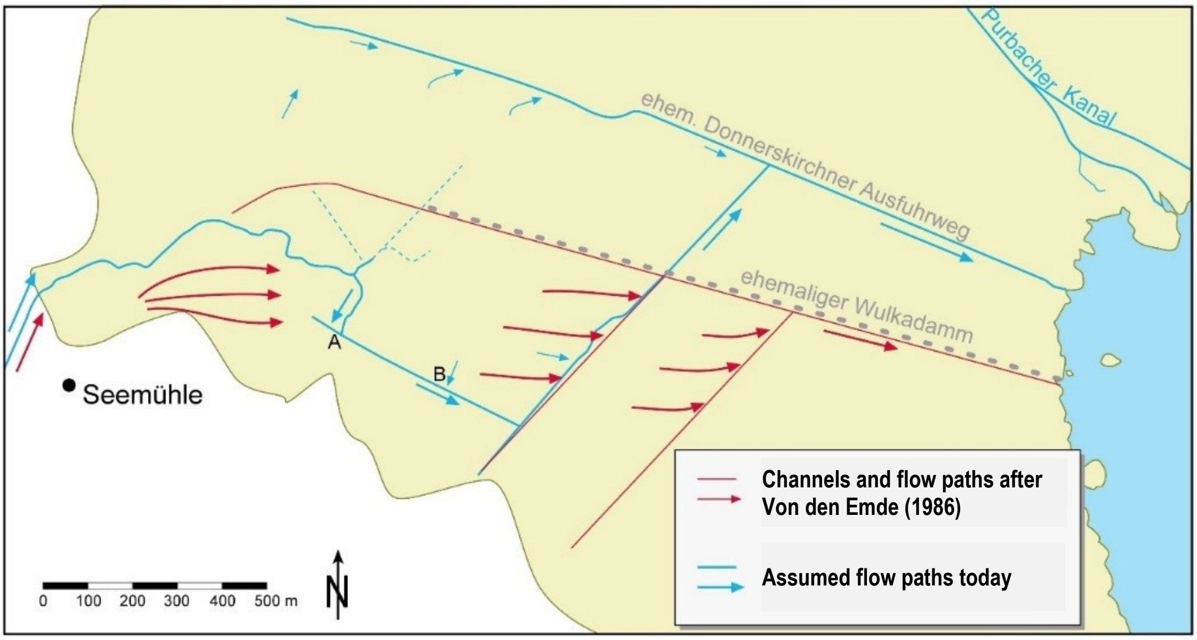


Figure 4. Pathways of the river Wulka through the reed belt of Lake Neusiedl in the 1980s (after Von der Emde et al. (1986)) and currently assumed pathways.

of the reed bed in the open lake. At least for 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.)

However, 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.

2.2 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 is not a homogeneous or even monotonous habitat but is characterized by 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 sediment 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 the large open water areas are characteristically found in the inner reed belt areas near 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. In the above mentioned broad band of dense reed beds lies the so-called lake dam, a sediment elevation, which stems from earlier input of lake turbidity and deposition of fine sediments in areas of low turbulence. Unfortunately, the data on the height of the lake wall in different areas of the reed belt are not sufficient to draw a consistent picture of its temporal-spatial changes. The analyses of E. Csaplovics (Report 2), however, at least show the range in the measurements of the 1980s and the ones from the GeNeSee project (Figure 5).

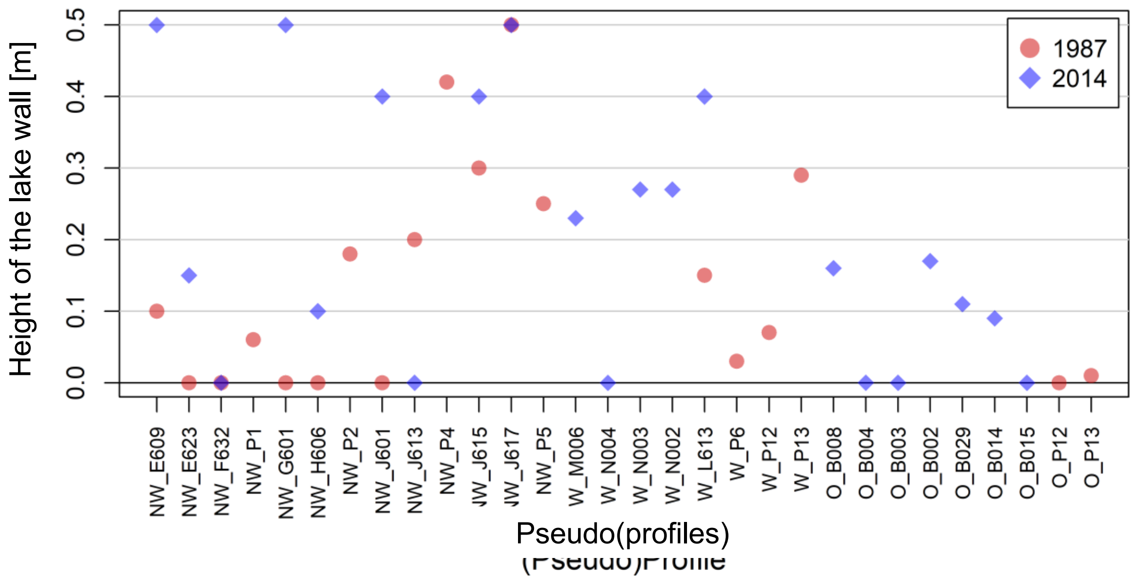


Figure 5. Height of the sediment dam at several profiles and pseudo-profiles at the lake reed boundary (from chapter 3 in Report 2 "Reed structure and morphology").

The numerous artificial channels are openings through 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, occur. 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 the Neusiedler See. In areas that are not connected to the open lake at all or only via very long channel paths, the concentrations of dissolved water constituents can be three times higher as compared to 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 ion equilibrium and 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 variations. A consequence of the reduced exchange with the open lake are intensified degradation processes in the 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 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 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 were 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 fish coenoses 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 and well connected to the lake.

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.

2.3 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 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 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 6).

Of particular interest for the exchange processes are the *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 level in north-south direction. The east-west orientation of the *seiches* is also subject to wind, which, due to the short distance, does not occur in a daily rhythm, but in waves usually between half an hour and a whole hour.

■ *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

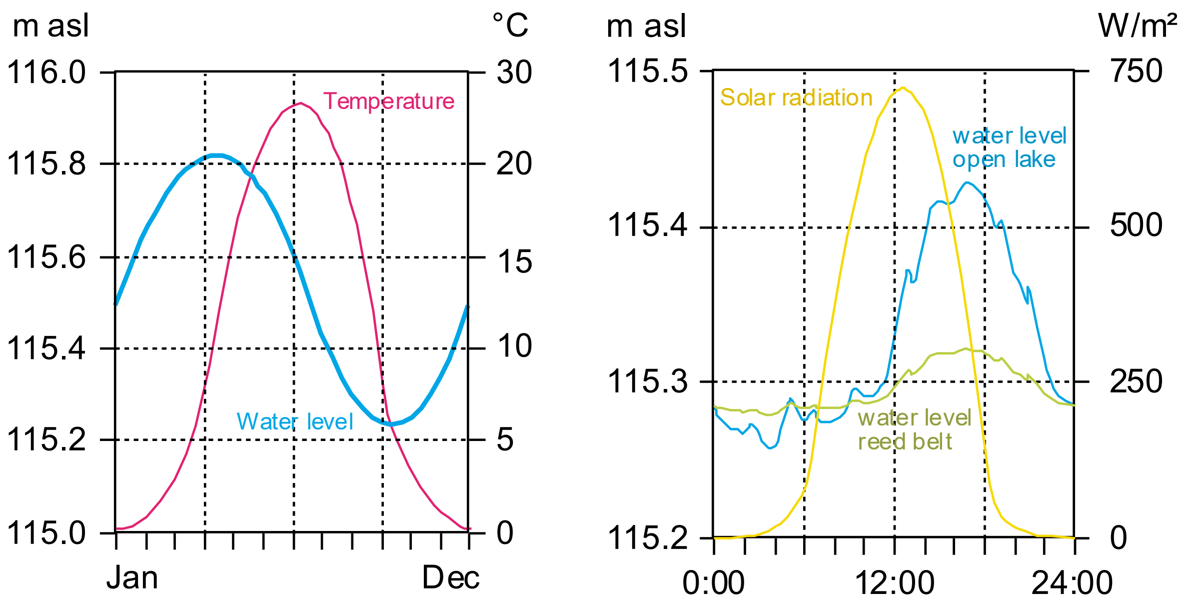


Figure 6. Scheme of main rhythms at Lake Neusiedl. Left: seasonal with water level and temperature, right: diurnal with typical wind event and corresponding seiche movement, and global radiation.

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) the case is probably due to the fact that new sediment (especially Ca-Mg-carbonates) is generated continuously 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 approaches (overflow *versus* shaking tests) allow the conclusion that the conditions at the sediment surface is 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 near Mörbisch there is a higher – 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, 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 and a still existing "permeability" (expressed by the Manning-Strickler coefficient of k_s=4 $m^{1/3}$ s^{-1}) of the overflowing 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 7) 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").

In the channels, surprisingly high **flow velocities** of up to several decimetres per second are achieved during strong winds and corresponding water surface displacements. With an assumed channel cross-sectional area of 2 m^2 (5 m width × 0.4 m depth), this corresponds to a flow rate of up to 1 m^3/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 7 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") this corresponds to a water transport of >14,000 m^3!

The **duration of the inflow and outflow phases** can be easily read from video recordings and from the data of the monitoring stations. The events can last for several days (see Figure 7) but can also be very short (*e.g.* a few minutes). The latter can be seen in the unsteady, jagged course of the water level, *i.e.* flow phases with (relatively) high flow velocity and rest phases in which the flow direction is reversed 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.* Illmitz height, outer edge to the open lake between monitoring site IL3 and the so-called Zander Bay, see Report 3) 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 increasing "clogging" of the channel. The process of **silting up of the reed channels** then accelerates until the water exchange will stop. 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, monitoring site IL8 (see Report 3) as well as in the fishing channels in the conservation zone of the national park in the southern part of Lake Neusiedl (*e.g.* the so-called Thell Channel), which have not been maintained for a long time. This development can be rapid and take 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 modelling (see Report 1 "Hydrology").

The situation described above with a water transport of more than 14 000 m^3 over two to three days was found in an area with **large open water areas in the inner reed belt**. Such areas are found *e.g.* at Illmitz and Mörbisch. For the Mörbisch area, the maximum daily load through one channel was estimated at 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 lead to an increased sedimentation in the open lake, *i.e.* in bays and in the protected lee behind reed islands. Observations of major 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 analyses of 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 in the direction of the channel and thus literally "pushes" the turbid lake water into the reed belt. Most of the channels at Lake Neusiedl 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.

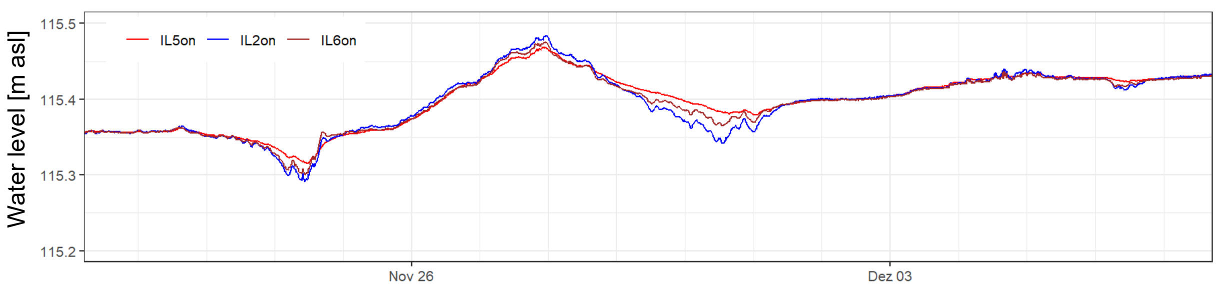


Figure 7. Water level at three monitoring stations in the reed belt of Illmitz between 22 Nov and 7 Dec 2018. Station IL5on lies in a large, open brown-water area with >14 ha; a rise of water level of 10 cm corresponds to a water inflow of >14 000 m^3.

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 (and particle-bound 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 the 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 a raising of the lake dam over the past 20 to 30 years could not be proven with certainty due to a lack of survey data in the reed belt (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.

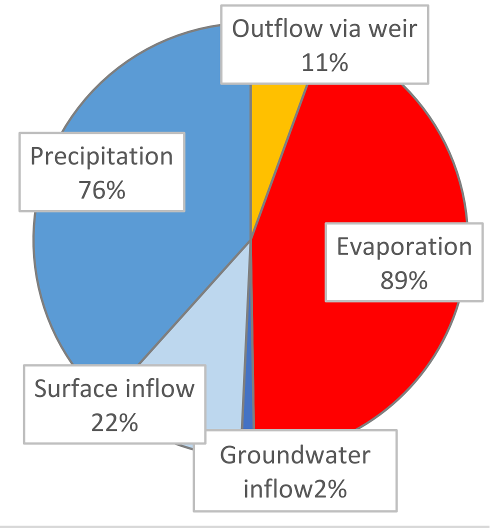
2.4 Loads of sediment, nutrients and pollutants

2.4.1 Water balance

Total water balances for Lake Neusiedl 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. 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. 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 8 & Figure 9, Table 2).

Water balance 1965–2018, mean values in mm/a	
Precipitation	579
Surface and groundwater inflow	180
Sum +	759



Evaporation	667
Outflow through Hanság channel	84
Sum –	751

Figure 8. Water balance of Lake Neusiedl 1965–2018 (Amt Bgld. Landesregierung, Abt. 5).

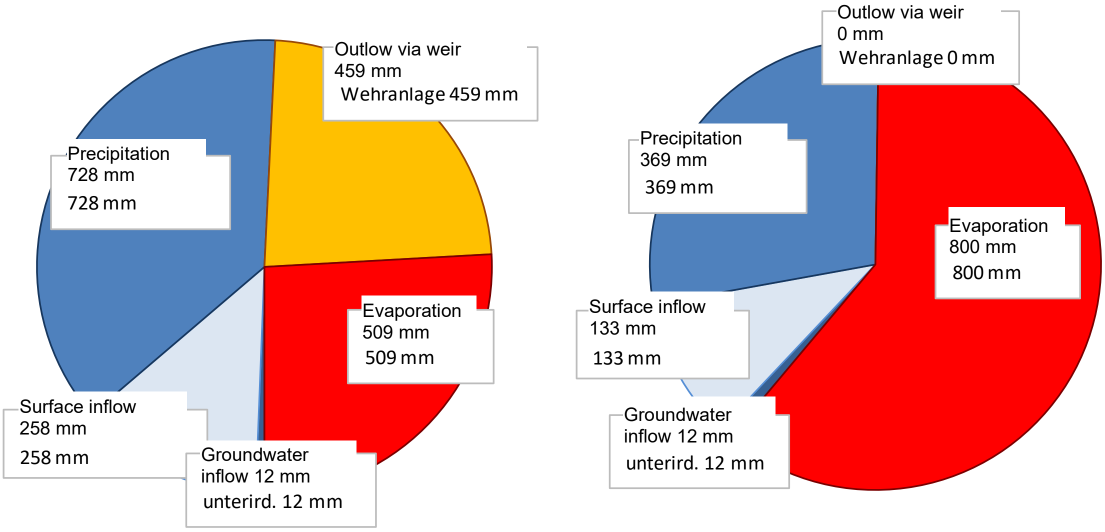


Figure 9. Water balance of Lake Neusiedl in characteristic years. Left: 1996, right: 2003 (from: Wolfram *et al.* (2014)).

Table 2. Water balance of the Lake Neusiedl 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 shown in Figure 10, which shows a significant rise of the lake level and less variability.

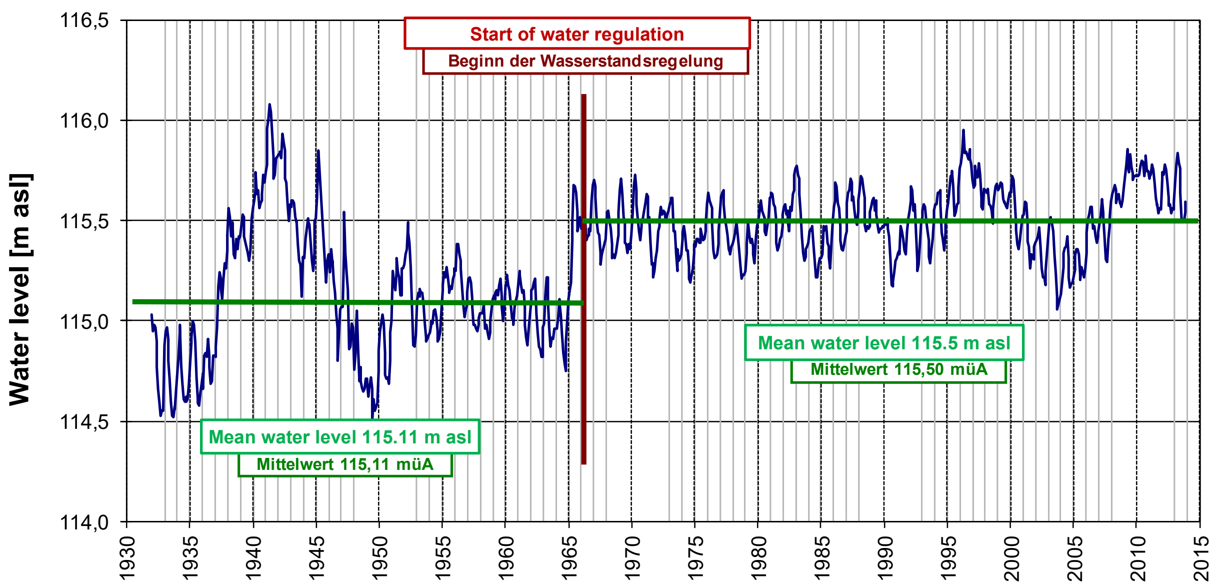


Figure 10. Hydrograph of the lake water levels 1932–2013. Source: Amt der Bgld. Landesregierung, Referat Hydrographie.

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 equalization or change with regard to the water balance. There is one thing the investigations clearly show: The area of Lake Neusiedl and its surroundings are highly sensitive and vulnerable as regards water management issues.

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

Lake Neusiedl

- *Since the water balance is the difference between two approximately equal values (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).*

2.4.2 Suspended solids

Preliminary note

The following diagram serves as a rough estimate 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 convey orders of magnitude to assess the importance of the individual loads.

■ *Input*

The total input of suspended sediment from the **Wulka** into Lake Neusiedl over the last 20-30 years (1992-2018) was **3 890t/a (mean)** with a range of 740 – 24 230 t/a (*cf* Chap. 3.1 in Report No. 3 “Physico-chemical parameters and pollutants”). The high variability is evident not only when comparing different years, but also at the level of daily loads. These are usually in the range of 1–5 t/d. During a severe flood event with suspended matter concentrations >1 000 mg L^{-1}, the turbidity load of the Wulka on a single day can exceed the load of an entire – low-discharge – year (see Figure 11).

As an example, Figure 12 shows the course of the concentration of suspended matter and the load of suspended matter during a strong flood (>20 m³/s) in May 2019. The maximum concentration of suspended matter at Seehof (measured at the water quality measuring station WU4) was over 3 500 mg L^{-1}; within one day, over 2 000 t of suspended matter were transported towards the lake (concretely: into the reed belt). Unfortunately there are no discharge values from the outlet of the Wulka at the outer reed edge to the open lake, nevertheless, the concentrations of suspended matter at the monitoring station WU1 show that only a small part of the solids from the Wulka actually entered the open lake during this event. Even in the case of strong floods, the solids load from the catchment area thus remains for the most part trapped in the reed belt. They reach the lake basin, but not the open lake.

As obvious as the difference between input into the reed belt and output into the lake is at high flows and loads, the comparison is uncertain at low flows. However, from the available measurements of suspended matter it can be concluded that even at low water levels of the Wulka, a significant amount of suspended matter settles in the reed belt; however, this is only a very small fraction of the total load.

According to expert estimates, the proportion of the Wulka's solid matter load reaching the open lake is estimated to be around 3% of the loads at Seehof.

In addition to the Wulka, there are also **other input paths** from the catchment area into the lake to be considered. The most important one is probably the Aeolian load. Measurements taken in the 1980s showed an average airborne dust concentration of 47 µg m^{-3}, which was about 1000 times higher than the phosphorus concentration (55 ng m^{-3}) (Malissa *et al.* 1986). Based on the measurements of Malissa *et al.* (1986) in the mass balance of Wolfram *et al.* (2011), the phosphorus input from the air as dry deposition was estimated to be about 3 t/a in the period 1992-2009. If one assumes the relation of the concentrations in the air also for the input, an estimated dust (=solid) input for the whole Lake Neusiedl of approx. 3 000 t/a results.

The input of solid matter via other tributaries (Golser Kanal, Kroißbach) and from sewage treatment plants is also estimated by analogy with the phosphorus balance. According to Wolfram *et al.* (2011), the discharge (in m³/s) from other tributaries amounts to about 17% of the load of the river Wulka, that from wastewater treatment plants (after 2001, *i.e.* after the major changes in wastewater treatment in the Neusiedler See catchment area) to about 2% of the total load of the river Wulka. As an approximation, these shares are also applied for the mass balance of the tributaries and the WWTPs, which discharge into the reed belt. As for the Wulka, a 97% retention of solids is assumed.

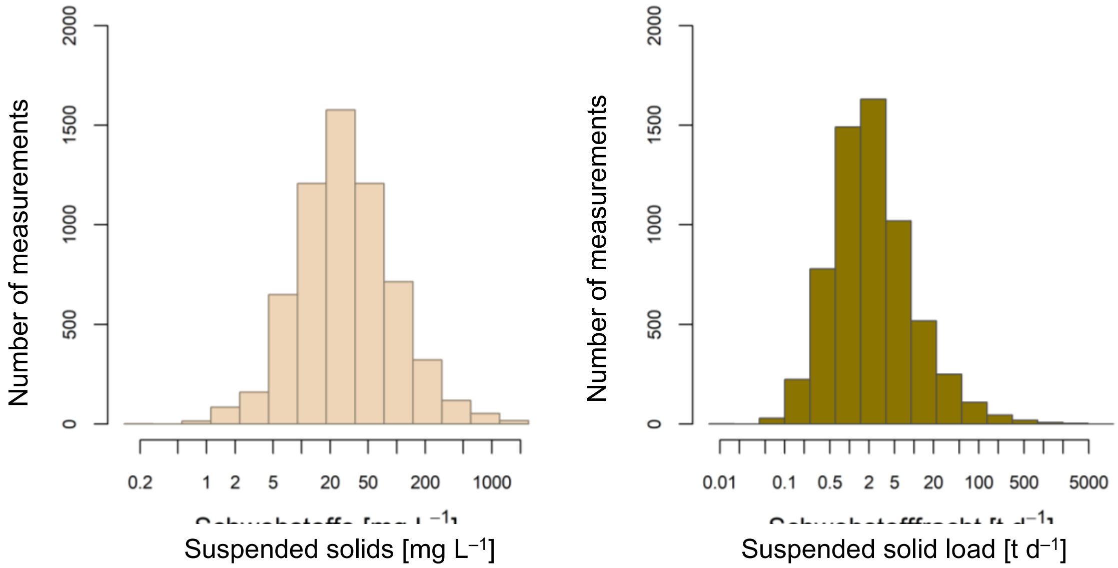


Figure 11. Histogram of suspended solid concentration (left) and load (right) in the river Wulka at Schützen/Geb. in the period 1992–2018. Source: Amt der Bgld. Landesregierung, Abt. 5.

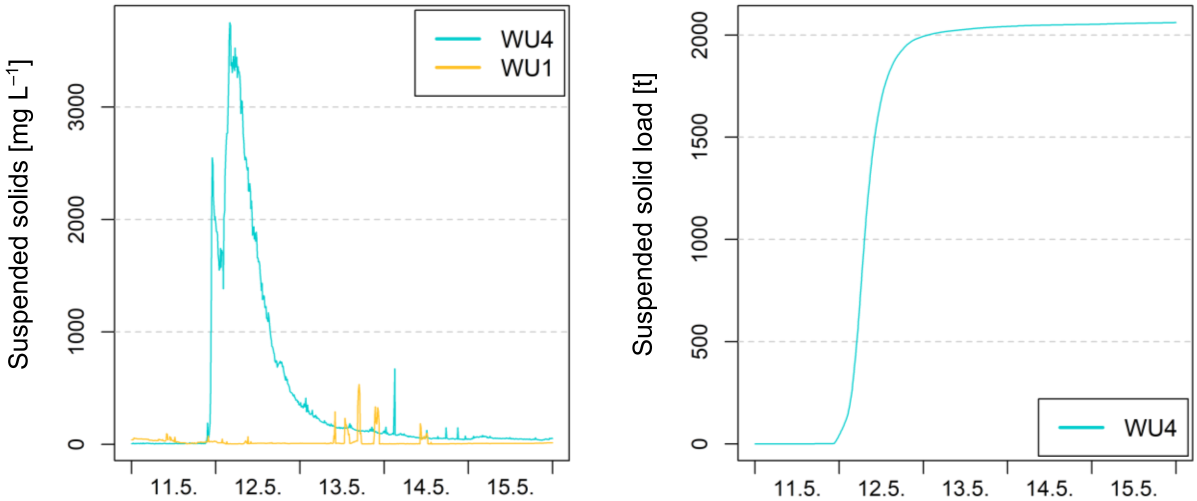


Figure 12. Suspended solid concentration (left) at the water quality stations WU4 (river Wulka at Seehof) and WU1 (Wulka inflow at the reed edge to the open lake) and cumulative load of suspended solids at the site WU4 (right) during a flood event in May 2019 (daily average on 12th May 2019: 11.1 m³/s).

- *New formation of sediment („Kalkschlamm“)*

As known from previous studies, a considerable part of the sediment in the lake is formed by precipitation processes. To quantify this amount is very difficult. The following estimation gives an impression of the order of magnitude of the carbonates formed, although the derivation here is limited to calcium for simplification (Table 3).

Table 3. Estimation of newly formed sediments as calcite ($CaCO_3$; dry mass). Calculations from Wolfram *et al.* (2012).

Newly formed sediment (Calcium)	
Calcium load of the Wulka (1993–2007)	2 126 – 6 095 t/a
Calcium load of other inputs (1993–2007)	919 –2 498 t/a
Calcium load of the output (1993–2007)	0 – 3 017 t/a
Remaining in the lake (1993–2007)	rd. 3 000 – 5 800 t/a
Conversion to $CaCO_3$ (Factor 2.5) = precipitation as lime mud ("Kalkschlamm") **newly formed sediment annually as Calcium-carbonate**	**7 500 – 14 500 t/a**

It is based on the difference between calcium input and output as well as the finding that the calcium content in the open water remains approximately the same in the long term, *i.e.* despite clear seasonal fluctuations and regardless of the dependence on the water level (see Wolfram *et al.* (2012)), there is no increasing or decreasing trend of the Calcium concentration in the lake. The difference in the loads, *i.e.* the calcium remaining in the lake, can therefore be assumed as sedimentation.

Besides calcium, magnesium is also involved in sediment formation (Krachler 2006; Preisinger 1979), but magnesium salts have a higher solubility. This can be seen, among other things, in the significantly higher Mg concentrations in the lake as compared to calcium, and also in the concentration in the lake (factor *af* as ratio of the concentration in the lake to the concentration in the inflow; *cf*. discussion in Chap. 5.3 in Report No. 3):

		Ca^{2+}	Mg^{2+}	
Input from Wulka (Mean value, site WU1, n=13)		98.0	43.5	$mg\ L^{-1}$
Open lake	(Mean value, site close to reeds IL1, n=13)	16.5	125	$mg\ L^{-1}$
	(Mean value, site close to reeds MO1, n=13)	17.6	128	$mg\ L^{-1}$
Factor *af* (Concentration)		0.17–0.18	2.89–2.95	

Nevertheless, magnesium also contributes to some extent to the sedimentation of the carbonates (Fussmann *et al.* 2020). If we include also silicate precipitation, the total amount of internal (non-organic) sediment formation is therefore somewhat higher than shown in Table 3.

Organic production (reed)

The estimation of the production of organic material and its contribution to the formation of sediments goes beyond the objectives of the project REBEN. However, there is no doubt that part of the sediment is of organic origin. It can be assumed that the non-mineralized organic material is mainly accumulating in the anoxic reed bed sediment.

The following figures should give an idea of the order of magnitude:

Burian *et al.* (1986) indicate the annually new (dry) biomass of the reed at Lake Neusiedl with 9–12 t/ha for uncut and 10–22 t/ha for cut areas. Based on an annual production of about 10 t/ha, a total annual production of 180 000 t dry matter is calculated. If one sets the harvest areas at 10% of the Austrian reed area (100 km²), the amount of reed taken out annually is about 10 000 t, which corresponds to the figures for the 1980s[1]. According to this, 170 000 t remain in the lake as annual production, form creased and old reed over the years and are finally shredded, degraded and mineralized. Depending on the proportion of non-mineralized reed, the contribution to the sedimentation and silting up of the reed belt in the long term can be estimated. With 1% or 5% of non-mineralized reed, this would be 1 700 or 8 500 t/a. These values are speculative and no data is available. In addition, to estimate the total production, the underground biomass of reeds (and for completeness, submerged macrophytes, planktonic and benthic algae) should also be considered.

- *Discharge via Hanság channel*

In the available mass balance studies no calculations on the export of suspended matter via the Hanság channel were carried out (Wolfram *et al.* 2007; Wolfram & Herzig 2013). Based on the mean discharge via the Hanság Channel (1992-2009: approx. 20 million m³) and the mean suspended solids concentration in the open lake (mean value at monitoring sites IL1 and MO1: 80.6 mg L^{-1}, n=26, project REBEN, see Report 3), the sediment load leaving the lake via the Hanság Channel in the long-term average can be estimated at approx. 1 600 t/a. As with the other loads, however, the range is very wide and ranges (over the period 1992–2009) from **0 t/a** (no discharge) to **11 450 t/a** (year 1996 with massive discharges).

- *Sediment removal by sediment dredging*

Information on the annual dredging in the sailing ports can be found in Report 2 "Reed structure and morphology". On average, about 20 000 m³ are removed per year. Depending on the sediment composition (water content, sediment density), this corresponds to about 5 600 to 8 100 t of solids, which are temporarily stored in sedimentation basins outside the lake and finally permanently removed from the lake.

In addition to the variable assumptions, there are also large fluctuations between years. While in **some years withdrawals are negligible**, in recent years they have reached **maximum values of 16 600 t/a**.

[1] Pannonhalmi (1984) estimated the annual yield of reed for the Hungarian part of Lake Neusiedl at the end of the 1970s / beginning of the 1980s with almost 14 000 t per yr on average.

- *Sedimentation and erosion in the open lake*

Displacements of sediments take place permanently in the open lake as an alternation of erosion and sedimentation. In times of low water levels and in areas with dense stands of submerged aquatic plants, a shift towards sedimentation can be assumed. If there is sufficient surface for wind attack, erosion may predominate.

The longer-term development is complex, as discussed in Report 2. In a comparison of the survey data 1987/1996 (Csaplovics *et al.* (1997) *versus* 2014 (Univ. Bodenkultur 2016) there is only one area with a positive vertical gradient (height increase, sediment accumulation) in the entire lake basin in the area of the open lake. This area is located exactly in the transition zone of various contrasting flow systems (circular in the area of Podersdorf-Hölle and in the middle of the lake at the height of Oggau).

For other areas, such as the profile Mörbischer Schilfinsel – Seedamm Illmitz/Seedamm Biological Station, a significant erosion and sediment transport can be assumed for the last 20-30 years. However, the mixture of inhomogeneities, some of which have contradictory and some of which have the same direction of action, due to different measurement approaches and certain divergent trends in situ, impairs the reliability of concrete statements on sediment dynamics. This applies all the more to displacements within the reed belt, for which no comprehensive statements on the height conditions are possible since the end of the 1980s.

- *Transport from the open lake into the reed belt*

In the project REBEN, the exchange between the open lake and the reed belt and the associated sediment transport was the main focus. During the wind event in autumn 2019, 195 kg net input of suspended matter was calculated for the channel north of the "station channel" (Biological Station Illmitz) in the course of wind-induced *seiche* movements. For a channel near Mörbisch a comparably high value was estimated, namely – as an average of the daily loads in September & October 2019 – about 180 kg. Taking into account the higher loads in spring of this year (stronger winds, higher water level), the total net inflow via the **channel near Mörbisch** can be estimated at **about 330 t/a**.

The **extrapolation** to the **entire lake** is naturally connected with very large uncertainties. It was carried out based on the experiences of the detailed observation in the channels at the heights of Mörbisch and Illmitz as well as the hydraulic modelling for the entire test area of Mörbisch and Illmitz. Two calculation approaches were chosen for the estimation:

Approach a) Extrapolation using the digital terrain model (DTM)

- Area (pools) in the inner reed belt, which can be "assigned" to the channel at Mörbisch, which was analysed in detail: 25 ha

- Total open water area in the reed belt (calculated on the basis of the reed-water layer created and provided by Elmar Csaplovics): 11.7 km² (47 times the detailed area at Mörbisch)
- Proportion of open water areas in the reed belt connected to the lake via channels (estimated value after analysis of the DTM and verification by means of satellite orthophotos / Google Earth): 49% (570 ha well connected, 600 ha not connected).
- Extrapolation of the results of the channel Mörbisch to the whole reed belt in Austria (factor 23.5): 7 755 t/a
- Estimated value for additional load in Hungary (30% of the load in Austria): 2 327 t
- Total load: **10 082 t**

Approach b) Estimated values according to expert judgment based on the analysis of satellite images / Google Earth, taking into account reed structure and number/form of channels)

- Reed belt area Mörbisch to state border (10x channel Mörbisch): 3 300 t/a
- Reed belt area Rust: 1 000 t/a
- Reed belt area Oggau: 500 t/a
- Reed belt area Donnerskirchen (Wulka mouth): 0 t/a
- Reed belt area Purbach (northern Wulka channel): 100 t/a
- Reed belt area Breitenbrunn: 100 t/a
- Reed belt area Winden to Weiden: 150 t/a
- Reed belt from Illmitz to the marina and resort of Illmitz: 1 000 t/a
- Reed belt area Illmitz resort to state border: 100 t/a
- Reed beds Hungary: 3 000 t/a

Total: **9 250 t/a**

In total, the estimated shift of fine sediments from the open lake into the reed belt amounts to between 9 250 and 10 082 t/a, depending on estimates. This estimate is valid for the entire lake at medium to low water levels (as was the case during the Project REBEN) and for the current network of channels. For estimation under changed conditions (channels, water level) see Chapter 3.

Internal sediment displacements due to channel restoration

In the course of channel maintenance, sediment is dredged out of the channels and deposited alongside, which over time has led to the formation of dams along the channels. These dams heighten and compact with each restoration measurement; older dams are now covered with willows and other woods (Figure 13).

The estimation in Table 1 is based on rough assumptions (*e.g.* depth of the sediment sampled, sediment composition). As the length of the channel excavation works varies considerably between different years (2.9–40.3 km, average 16.6 km), the range of estimated sediment abstraction is also very large at 450 – 9 070 t/a (Table 4).

The dredging along the channels does not remove the sediment permanently from the lake. Nevertheless, the dams are usually above a level of about 116 m ü A, and thus above the water level. The sediment deposited there is therefore taken out of the cycle; it is excluded from new erosion and transport and, as the material dredged from the sailing ports, it can be regarded as permanently removed from the system.

On average, the total amount of sediments dredged in the channels is less than that from sailing ports and bathing areas. However, the values given in Table 4 only refer to the Austrian part of Lake Neusiedl.

Figure 13. Recently dredged sediment (left) and trees on an older section of a dam (right) along a channel near Purbach (2nd April 2019).

Table 4. Estimation of sediments, which are dredged annually (and deposited alongside of the channels) in the Austrian part of the reed belt (dry mass).

Restoration of channels	
Total length of the channels maintained [1)]	2.9 – 40.3 km
Mean width of the channels	5 m
Depth of the sediments dredged (estimation)	10 cm
Water content 70–75%, sediment density 1.25–1.5 g cm^{-3}	
Total amount of the sediment dredged from the channels	**450 – 9 070 t/a**

[1)] Average over the period 2004–2019: 16.6 km

Overview

The listed quantities of solids introduced into the lake, formed in the lake or relocated within the lake are summarized in Table 5 below. As mentioned above, these figures do not allow for a true mass balance, mainly due to uncertainties in assumptions and the high temporal variability.

Table 5. 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

Despite all uncertainties, the following statements can be derived from this compilation:

1. The solids introduced into the lake 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 has a lasting effect on the structure and character of the reed belt.

The numbers in Table 5 are shown as a flow chart for visualization in Figure 14. It must again be noted here that the estimates do not result in a balanced balance sheet. This was not to be expected in view of the numerous assumptions, fuzziness and uncertainties. The "balance sheet items" are rather intended to give an impression of the magnitude. In particular, it should be taken into account that some balance sheet items were estimated for the whole lake (*e.g.* lime mud or "Kalkschlamm"), others only for the Austrian part (*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 Lake Neusiedl. The general situation, however, can be described.

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)[2] 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).

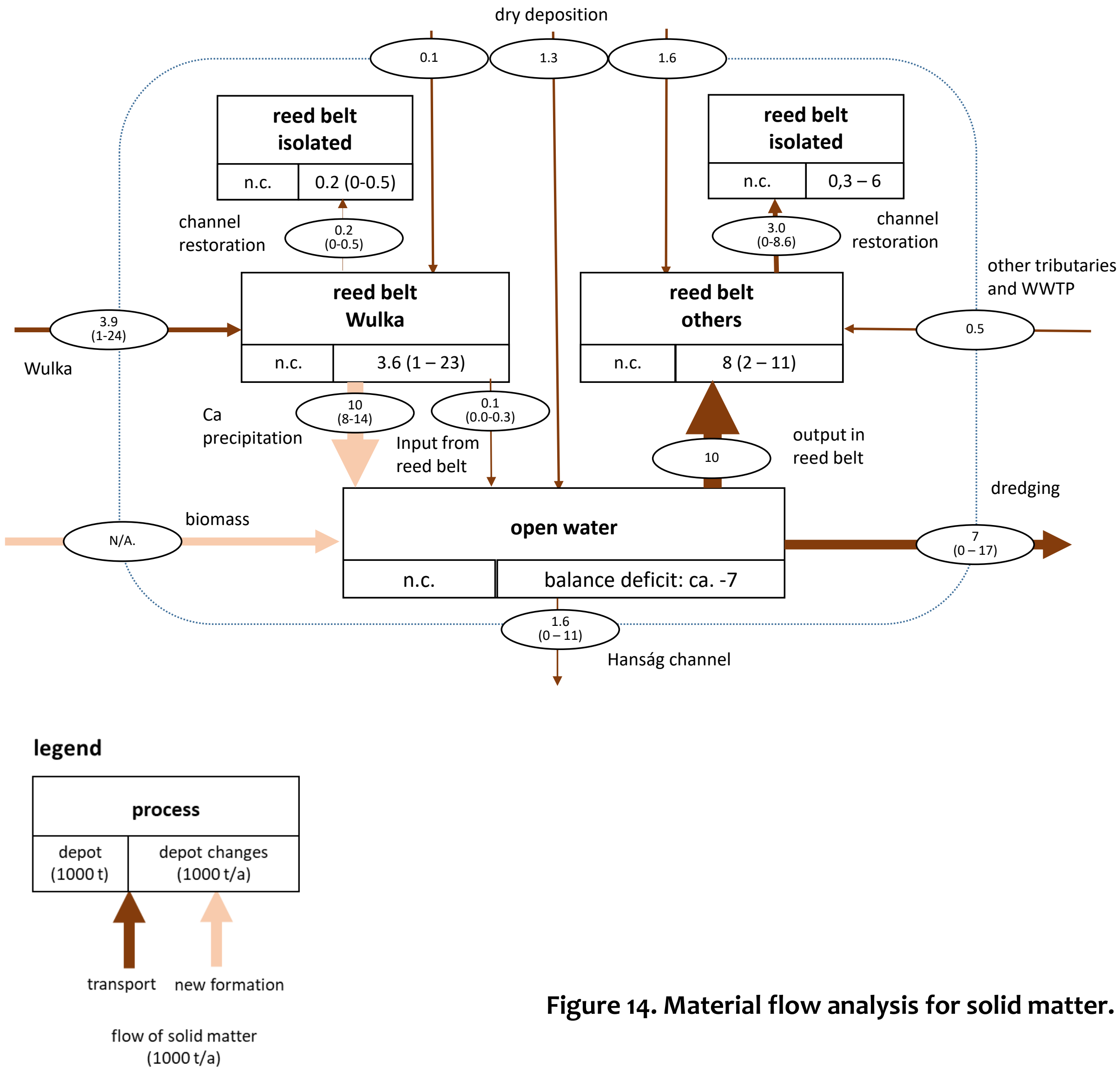


Figure 14. Material flow analysis for solid matter.

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[2] Aus dem Projekt GeNeSee liegt nur für den offenen See eine Angabe zum Schlammvolumen mit 54,7 Mio m³ vor (Univ. Bodenkultur, 2016).

For further considerations of the mass balance and the question of the sedimentation of Lake Neusiedl there are two open questions:

The first concerns the *sediment elevation* in the reed belt. Since the GeNeSee project was practically only able to make statements for the open lake, it was necessary to create an approximate DTM for at least the three test areas on the basis of additional photographs in the project REBEN; this DTM had to be additionally adapted for the hydraulic modelling and corrected in places within the model software. However, the question of the long-term development of the reed belt remains open and should be given priority in future research at Lake Neusiedl.

The second point concerns the *reeds*. The last extensive research on the growth of the reed plant dates back almost 40 years (Burian *et al.* 1986) and was mainly focused on the production and partly also on the economic utilization of the reed. With regard to the sedimentation of the reed belt, not only the production (using newer methods and under the current conditions), but also the decay and mineralization of the organic material should be investigated – questions that also touch on questions of nutrient dynamics and thus lead to the following chapter.

2.4.3 Nutrients (phosphorus)

The following considerations on the nutrient balance of Lake Neusiedl 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 way of nutrient deposition was unclear in detail, but also the location. Here, the investigations of the project REBEN can contribute important new findings.

- *Input*

The total phosphorus discharge into Lake Neusiedl was calculated to be about 80 t in 1982/83 (only for the Austrian part) (Malissa *et al.* 1986; Stalzer *et al.* 1986). In the early 1990s, external loads (incl. the catchment area of the Kroisbach in Hungary) were less than 30 t per year (except for a peak in 1996). In the dry years after 2000, the external annual load even decreased to 10–13 t, only to increase again in the course of increased water flow of the Wulka and correspondingly higher loads via this input path.

In the project REBEN detailed measurements of different phosphorus fractions of 13 dates are available (in the following given as mean value ± 95% confidence interval). They originate from the Wulka near Seehof (WU4), from the reed belt (WU2) and at the edge to the open lake after flowing through the reed belt (WU1):

	WU4		WU2		WU1	
SRP [µg L^{-1}]	88	± 17	114	± 23	110	± 28
DP [µg L^{-1}]	114	± 18	138	± 23	134	± 31
PP [µg L^{-1}]	49	± 23	31	± 12	17	± 7
TP [µg L^{-1}]	164	± 38	169	± 31	151	± 33

Based on these measurements, the proportion of dissolved phosphorus in the total phosphorus concentration at the site WU4 was 70%.

From the data of the h2o database, the following concentrations and relations were calculated for the site Seehof (mean values ± 95% confidence interval):

	1991–2020			2010–2020		
SRP [µg L^{-1}]	119	± 1	54%	68	± 1	47%
DP [µg L^{-1}]	169	± 3	76%	101	± 1	71%
TP [µg L^{-1}]	222	± 7	100%	143	± 1	100%

The figures suggest a slight decrease of the particulate fraction of the total phosphorus in the Wulka, but represent essentially a low water discharge. However, as the measurements with the water quality stations (online measurements) show and known from previous investigations, flood events contribute mainly to the total phosphorus load. The largest part is transported in particulate form into the reed belt.

As explained in detail in Report 3, the total phosphorus concentration does not change significantly when passing through the reed belt (at least at low and medium discharge, but probably also during floods), whereas the particulate fraction decreases significantly and the dissolved fraction increases significantly (statistical test on the level of individual dates, *i.e.* with associated samples).

The mean concentrations were determined at low to medium water levels of the Wulka. If one refers these to a low water year of the Wulka (*e.g.* 2003 with nearly 22 million m³) the theoretical annual load can be estimated approximately. For the year 2003 it is 3.6 t/a, which corresponds almost exactly to the value determined for this year in the detailed mass balance by Wolfram *et al.* (2012) (3.5 t/a). Based on the data from the project REBEN, however, this value can be divided approximately between the two main fractions (particulate PP, dissolved DP) and, in addition, the loads can be given not only for the Wulka before entering the reed belt (before RB), but also at the border to the open lake (after RB):

	before RB	after RB	Difference
TP [t/a]	3.6	3.3	−0.3
PP [t/a]	1.1	0.4	−0.7

DP [t/a]	2.5	2.9	+0.4

The total load of 3.6 t/a in this year is at the lower limit of the range calculated in the detailed mass balance (but only for total phosphorus) for the period 1992–2009 (3.5–39.8 t/a, MW 13.6 t/a). This again underlines the importance of strong floods for the nutrient transport.

While the data from REBEN provide data on the annual loads in years with low discharge and allow calculations for different fractions (particulate vs. dissolved) as well as before and after the reed belt passage, the calculations from the detailed mass balance (by Wolfram *et al.* (2012)) provide an insight into the conditions including increased loads during floods, albeit only for total phosphorus and the Wulka before entering the reed belt. However, the two approaches can be combined – as summarized in Table 6 – by estimating the particulate phosphorus load approximately as the difference between the total load (from the detailed mass balance) and the dissolved phosphorus load (as product of the water load and a mean DP concentration of 100 µg L^{-1}.

Specifically, the following adjustments and assumptions were made:

- The total phosphorus load varies between 4 and 40 t/a according to the mass balance in the period 1992–2009. (A more recent mass balance is not available. However, the loads today are likely to be similar to those of about 10 years ago; at least the measurements of total phosphorus concentrations at Wulka Seehof do not indicate an increasing or decreasing trend according to the water status monitoring surveys [h2o database, unpublished evaluations]. The dissolved phosphorus concentrations, however, are likely to have decreased somewhat.)
- According to the approximate approach described above, the distribution of the phosphorus load in particulate : dissolved form is about 1 : 1 in the low water year, about 5 : 1 in the high water year and about 3 : 1 on average.
- The proportion of the particulate load retained in the reed belt is very high regardless of the discharge of the Wulka (see Figure 12). Less than 1 t/a reaches the open lake. Analogous to the solids, a retention of 97% is assumed.
- In contrast, high dissolved phosphorus loads from the Wulka (during floods) are likely to reach the open lake due to the shorter flow time through the reed belt at high discharge.
- The increase of dissolved phosphorus in wet years and high flows is not expected to be much higher than in a low water year. The data also do not show any noticeable seasonal fluctuations (in contrast to the 1980s). The increase is estimated at ca. 1–7 t/a.

- *Discharge via the Hanság channel; output by dredging and channel restoration*

Discharge via the Hanság channel (taken directly from the mass balance) as well as removal by means of dredging and channel restoration can be estimated more easily than the input situation. For the latter, the sediment output according to Table 5 and the phosphorus contents from the sediment analyses (Report 3) were used.

- *Transport from the open lake into the reed belt*

In the context of the mass balance, Wolfram *et al.* (2012) derived the net deposition of phosphorus in the sediment of Lake Neusiedl by calculation. In the period 1992–2009 it is 24 t/a on average, with a considerable variation between flood and low water years (6–53 t/a). The net deposition was calculated from the monthly deviations of the balance (inflows and outflows, changes in the actual content in the lake) on the other hand. Months with balance surpluses were called periods of net sedimentation, those with balance deficits were called periods of net release. The sedimentation can be seen mainly as discharge from the open lake into the reed belt; the conspicuous seasonal change of sedimentation and re-solution could be explained by the change of the water level and related processes.

It should be noted that in months with predominant sedimentation, of course, discharge from the reed belt into the open lake occurs and vice versa in months with net discharge not only dissolution processes but also sedimentation occurs. The monthly load rates only indicate the predominant process.

In the summarizing Table 6, the internal transport of phosphorus was estimated in two ways:

(1) A net deposition of 24 t/a on average was calculated from the mass balance. As mentioned above, a part of it already remains in the Wulka reed belt (3 t/a), a part is removed by sediment dredging (also 3 t/a); this removal had not yet been considered in the mass balance of Wolfram *et al.* (2012). The remaining load **(18 t/a)** is transported from the open lake into the reed belt (excl. the Wulka mouth). (Since in the material balance of Wolfram *et al.* (2012) the discharge by sediment dredging was not considered, there is a discrepancy in the balance, *i.e.* the discharge from the open lake - reed belt is to be set somewhat lower).

(2) At Mörbisch a suspended matter input of 550 t/a and a discharge of 220 t/a, thus a balance of 330 t, was calculated in a reed channel using the water quality stations (online probes). Extrapolated to the entire lake, this corresponds to approx. 13 000 t/a input, 5 200 t/a output and 7 600 t/a as balance or net input. This compares to a water load in the

Mörbisch Channel of 3.14 million m³/a as inflow and 2.85 million m³/a as outflow (balance 0.3 million m³). Extrapolated by the same factor, this results in an annual water load of 100 million m³ as input, 97 million m³ as output and 10 million m³ as annual balance. From the product of the water load with the particulate phosphorus concentration in the open lake (mean value of the sampling points IL1 and MO1, 66 µg L^{-1}, n=26) as input and with the dissolved phosphorus concentration in the reed belt (mean value of the sampling points IL2-5, MO2-4, 15 µg L^{-1}, n=91) as output, annual loads of 7 t/a input and 1 t/a output are calculated. Probably the input has to be set higher, because most of the sampling and measurements were carried out on calm to moderately windy days. Strong wind events with correspondingly high input of suspended matter and phosphorus into the reed belt are certainly underrepresented. Assuming an up to twice as high input (which seems realistic for peaks with several times higher P concentration in the open lake), the input is 7–14 t/a (mainly particulate), which results in a net input of **6–13 t/a** at the indicated output of 1 t/a of dissolved P. This value lies within the range of phosphorus deposition in the reed belt estimated from the mass balance.

Table 6 summarizes the phosphorus loads in tabular form, and Figure 15 also provides a visualization as a flow chart for the suspended solids. The most important results / findings from the load estimation are:

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 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 a little more than half of the total inputs in contrast to earlier (1980s) years with a higher share (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 however 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 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.

It is conceivable that the extent of nutrient release, *i.e.* the amount of dissolved phosphorus load from the reed belt into the open lake, is increased by mechanical disturbances, *e.g.* in the course of reed cutting, in the course of channel rehabilitation or by sediment dredging in marinas and bathing areas. How much these measures will lead to an increased nutrient availability in the open water of Lake Neusiedl cannot be estimated at present.

Table 6. 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 [3)]	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 [1)]	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

*) Values from the sediment mass balance of Wolfram *et al.* (2012). 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

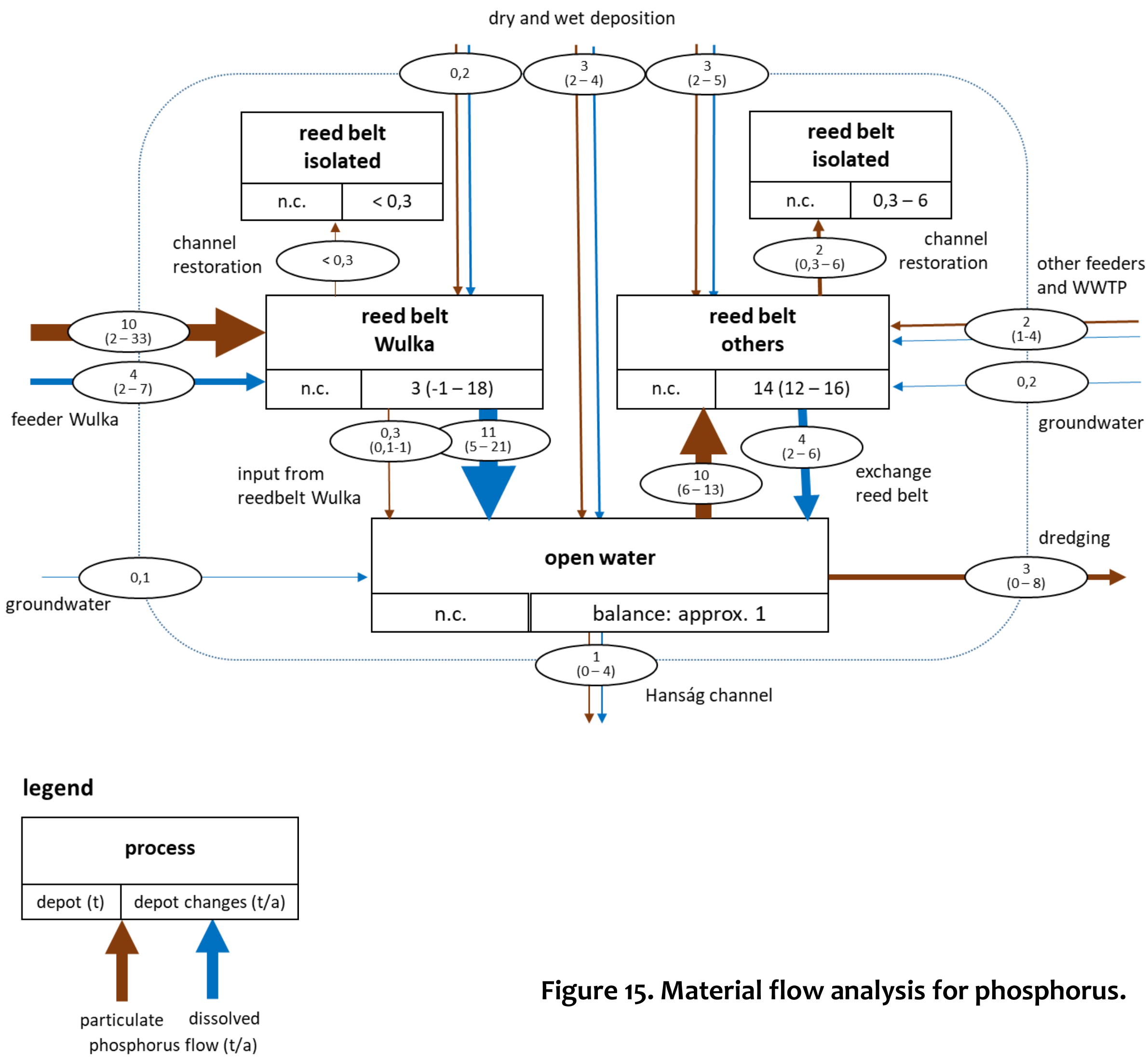

Figure 15. Material flow analysis for phosphorus.

2.4.4 Pollutants

■ *Concentration gradients*

While the loads of nutrients and solids into the lake have been an important object of investigation for a long time and therefore a high level of knowledge is available (*e.g.* Stalzer *et al.* (1986), Wolfram & Herzig (2013), Wolfram *et al.* (2019), which was further developed in the course of the project REBEN (up to the first material balances for solids and phosphorus, taking into account the exchange processes with the reed belt), the pollution of Lake Neusiedl with pollutants/trace elements has only been investigated to a limited extent so far (Wolfram *et al.* 2014). Therefore, the investigations on pollutants during the current project cannot build on a comparable expertise and are breaking new ground in several respects.

The first objective of the investigations on pollutants was to obtain information on the occurrence and fate of substances of different origin and with different fields of application and different environmental behaviour. Accordingly, the parameters were selected for investigation. However, monitoring compliance with the environmental quality standards (EQS) of the Ordinance on the Chemical Quality Objectives 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 quality standards. Also for lead in the open lake, indications of exceedance of EQS could be 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 investigated substances, a first assessment of the respective environmental behaviour in the lake and reed belt can already be made on the basis of the concentration measurements carried out in the Wulka before the inflow into the lake, in the Wulka after passing through the reed belt, in the open lake and in the areas of the reed belt near Illmitz and Mörbisch. In Figure 16, examples of the concentration changes are shown for some substances. Based on this illustration, possible behaviour patterns shall be discussed. The findings from the laboratory tests on adsorption and mobilization (Report 6 "Laboratory tests") help to understand the different findings.

Due to the large number of substances investigated, only a selection is shown in Figure 16. On the one hand, 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 were chosen 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", 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).

All the other substances investigated in REBEN, but not shown in Figure 18, are assigned to groups with similar environmental behaviour as the substances shown. Substance names in brackets indicate ambiguous results and uncertainty of the assignment. A comprehensive presentation of the measurement data of the project REBEN is given in Chap. 5 of Report No. 3 "Physico-chemical parameters and pollutants".

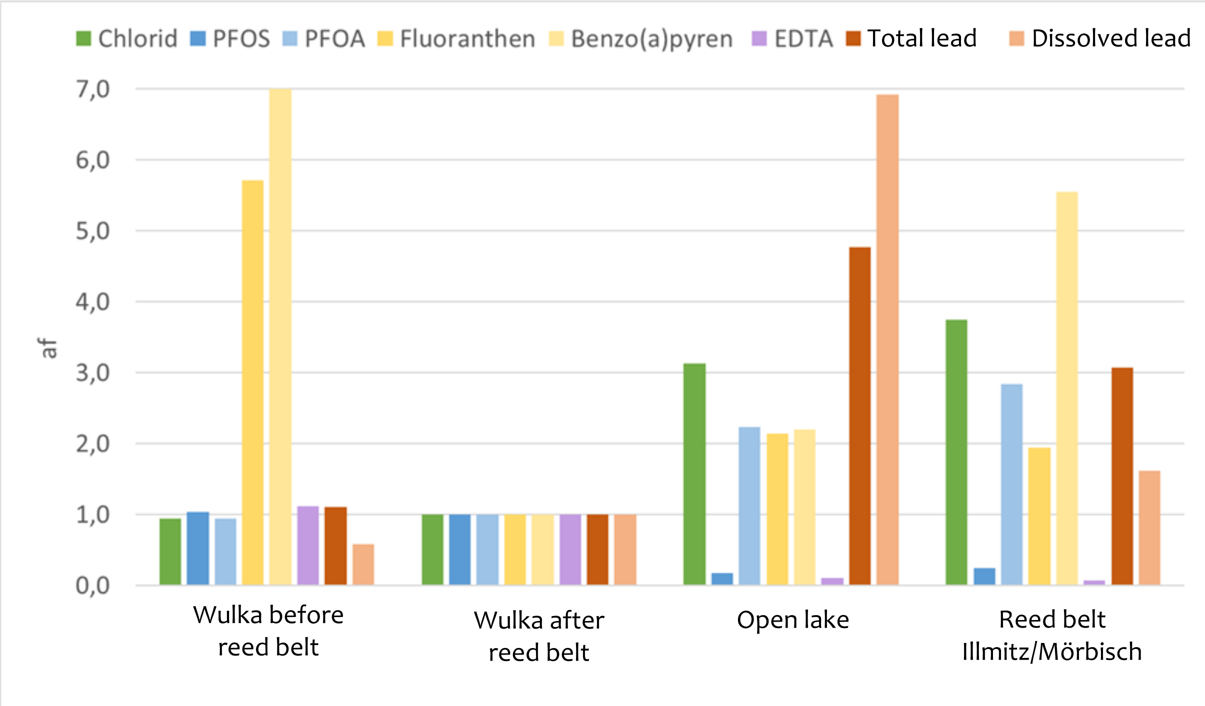

Figure 16. Enrichment or decrease factor (af = C_n/C_0) for selected substances. C_n means concentrations in each water phase and for C_0 the concentrations in the inflow from the Wulka reed belt to the open lake was chosen.

Chloride is not attributed to the pollutants or trace substances. In Figure 16 it is used as a well investigated substance as a reference for those substances which are largely persistent in the lake and the reed belt and are almost exclusively present in the water phase. The extent of the concentration is shown by the enrichment or depletion factor (*af* = C_n/C_0). C_n stands for the concentration in the respective water phase. C_0 does not indicate the concentration in the Wulka before the reed belt but in the Wulka after passing the reed belt. This is intended to better illustrate the processes in the lake and reed belt and not to hide them by processes in the Wulka passing the reed belt. For chloride it is shown that, as expected, the concentration does not change when flowing through the reed belt of the Wulka (*af* in the Wulka inflow is close to 1). In the open lake, *af* (*i.e.* an increase of concentrations due to evaporation exceeding precipitation) is about 3. In the reed belt, *af* increases to approximately 4 due to further concentration. Since this value can vary depending on how remote a monitoring site in the reed belt is (or how well or poorly it is connected to the lake via channels), for those monitoring sites where the pollutant analysis was carried out chloride was used as a reference parameter.

The polyfluorinated surfactant PFOA shows a very similar behaviour to chloride: no change in concentration in the Wulka when flowing through the reed belt, increasing concentration in the open lake and the reed belts of Mörbisch and Illmitz. PFOA is predominantly dissolved in the Wulka and is largely persistent in the lake and reed beds. However, the concentration increase of PFOA is slightly lower than that of chloride. Further investigated substances with similar behaviour are: the pesticide metabolite N,N-dimethylsulfamide; the poly- and perfluorinated chemicals PFPeS, PFHpA, (PFNA and PFHxA) and the (sweetener: acesulfame K).

The polyfluorinated surfactant PFOS shows no change in concentration when flowing through the Wulka Reed Belt. Only a very small proportion of its transport is particulate. In the lake, however, the concentration significantly drops. This would not have been expected at the beginning of the investigations, since these substances are considered largely persistent in the environment. In the reed belt of Mörbisch and Illmitz a slight increase in concentration is observed. Since the laboratory tests showed a clear adsorption of PFOS to the sediment, a discharge of PFOS by this route cannot be excluded.

EDTA in Figure 16 is the example of a substance that is subject to significant degradation or conversion under the environmental conditions of the lake. While no relevant reduction was found in the flow of the Wulka through the reed belt, the concentration in the lake and increasingly in the reed areas of Mörbisch and Illmitz decreases significantly. Furthermore, no evidence of storage in the reed sediments was found. It is therefore to be assumed that EDTA is extensively degraded or converted. Nothing can be said on the basis of the current state of investigation about the final products of such a conversion, so it can come to a complete mineralization but also to the formation of degradation products (metabolites). Further substances with this pattern of behaviour are: the active pharmaceutical ingredients carbamazepine, diclofenac and bezafibrate, the complexing agents NTA and benzotriazole, the pesticide metabolite chloridazone-desphenyl and possibly the (sweetener: acesulfame K).

Benzo(a)pyrene, fluoranthene belong to the polycyclic aromatic hydrocarbons (PAH). They are transported from the catchment area into the reed belt via the Wulka, mainly bound to particulates. Due to extensive particle retention on the way through the reed belt, these compounds are therefore largely retained together with the solids in the Wulka reed belt. In the lake there is a concentration increase (*af* approx. 2) which is in the range of PFOA and slightly below that of chloride, indicating the persistence of these substances. In the reed belt of Mörbisch and Illmitz, the existing measurement data show that there is no further concentration of fluoranthene. For beno(a)pyrene, however, *af* rises to > 5. This finding may serve as an indication of the importance of adsorption and mobilization processes, which play an important role here. Also relevant concentrations of benzo(a)-pyrene, fluoranthene in the reed sediments and the results of the laboratory tests indicate the importance of the reed sediments for the storage of these substances, but also a labile equilibrium of adsorption and mobilization, which already reacts to slight changes of the environmental conditions. Among the substances that show similar behaviour to benzo(a)pyrene, fluoranthene are the other higher molecular weight PAHs.

Lead as total lead and dissolved lead is shown in Figure 16 as an example of the heavy metals, all of which tend to behave similarly. In the reed belt of the Wulka no change in the total lead concentration can be found based on the existing data. However, this should be studied in detail in an extended data base. Since the concentration of dissolved lead increases significantly, the findings here should be similar to those for phosphorus: the retention of solids in the Wulka reed belt retains particulate lead. However, this concentration reduction is reversed for total lead by a dissolution of lead when passing through the reed belt. Furthermore, total lead and dissolved lead show a similar course at different levels: both show a significant increase in concentration in the open lake (*af* of Pb_{total} approx. 5, *af* of $Pb_{dissolved}$ approx. 7), which decreases significantly in the reed belt area (*af* of Pb_{total} approx. 3, *af* of $Pb_{dissolved}$ approx. 1.5). The data is not comprehensive enough to draw final conclusions. Nevertheless, the data are a clear indication of the great relevance of adsorption, storage in sediments and internal mobilization and desorption of heavy metals. Thus, the high concentrations that were found occasionally cannot only be explained with the input via the Wulka or the concentration typical for the lake. There is some evidence for mobilization from internal storage, as represented by the lake's solids or lake sediments. On the other hand, the lower contents in the reed areas of Mörbisch and Illmitz also indicate sedimentation and adsorption processes, which can lead to a reduction of the concentrations in the aqueous phase. However, a comprehensive understanding and quantification of these processes, which are heterogeneous in time and space, is currently not possible. However, it can be assumed that adsorption, sedimentation and mobilization processes in the reed belt are as relevant for the heavy metals and PAHs in the lake as the input from external sources such as the Wulka.

- *Loads*

For PFOS, PFOA and fluoranthene, essential material flows into and out of Lake Neusiedl 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. For the inputs and discharges, the lake and the reed belt are considered as one system. Changes in the system's storage indicate a retention in the reed-belt reservoir.

Regarding pollutants, it was not distinguished between the Wulka region and the rest of the reed belt.

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 range of the data is given. The figures only indicate 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 in the lake. Thus, the input is calculated with the inflows and the discharge with the outflow via the Hanság channel. In addition, estimates of atmospheric deposition from Zessner *et al.* (2019) are used to consider this input path in the balance. As Figure 17 (left) shows, for the PFOS, aerial deposition adds to the input from inflow in the same order of magnitude. The discharge of PFOS via the outflow in the Hanság channel is very small as 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. If we assume the same concentration of PFOS in the suspended solids as those measured in the suspended matter of the Wulka or in the sediment of the lake (ca. 0.2 µg/kg dry mass), and assume a transport of solids from the lake into the reed belt in the order of 10 000 t dry mass per year (*cf* Chapter 2.4.2), it turns out that the path from the lake to the reed belt is of little relevance and the load is in the same range as the load via the Hanság effluent. The same applies to a possible discharge via fish consumption by water birds or fishing. Even in the unrealistic case that the annual fish withdrawal would correspond to the fish stock of about 600 t (data from Nemeth *et al.* (2003)), the PFOS concentrations in biota (Tab. 1) result in a withdrawal via this path that would be significantly below 0.01 kg per year.

Since the authors of this study consider a relevant discharge of PFOS via reed cutting to be also very unrealistic, 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). However, the results of the adsorption tests show that PFOS can be further eliminated from the aqueous phase of the lake. Thus, as described in the Report 6 "Laboratory Tests", a relevant elimination of dissolved PFOS by adsorption from the lake water to the lake sediment can take place.

Overall, the PFOS balance of Lake Neusiedl 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 fate in the environment is unknown. Furthermore, an adsorption of PFOS to the reed sediment can also provide a removal path from the open lake.

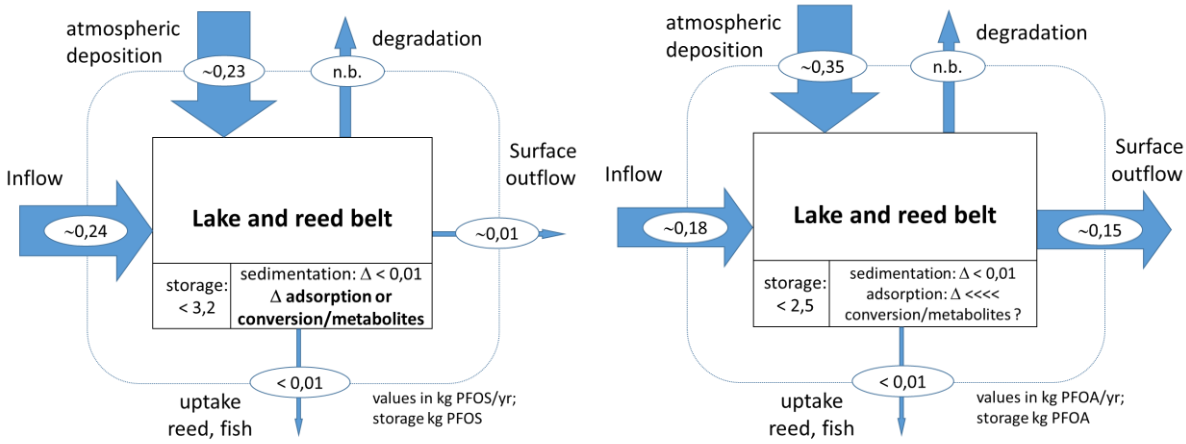

Figure 17. Estimation of a substance balance (kg/a) of the lake Neusiedl for PFOS (left) and PFOA (right)

The situation for PFOA is similar to PFOS (Figure 17, right). The input via deposition is likely to exceed that via surface tributaries, and the estimated discharge with the Hanság channel cannot fully explain the fate of the inputs into the lake. Differently, the elimination of PFOA is much less extensive than for PFOS, the concentration in the lake is significantly higher than in the Wulka, and thus the discharge via the Hanság channel is similar to 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 Report 6 "Laboratory Tests". Thus, at least the substance load, which enters the lake via aerial deposition, could not be found in the lake effluent 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.

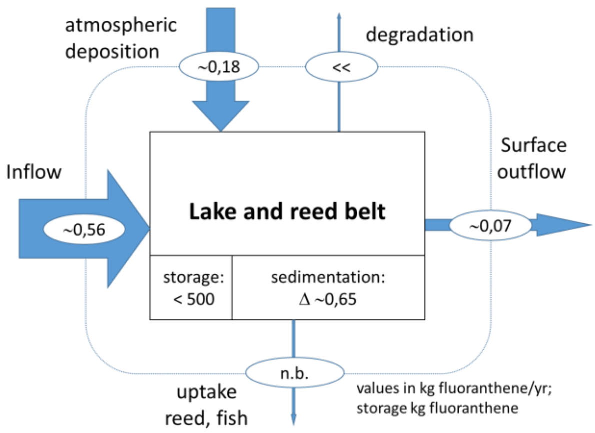

Figure 18. Estimation of a substance balance of the lake Neusiedl for fluoranthene

At first glance, the balance sheet for fluoranthene (Figure 18) also resembles that for PFOS – an input via inflow and deposition on one hand and a significantly lower load via outflow on the other hand. Thus, the lake also serves as an effective sink for fluoranthene. A closer look, however, reveals a clear difference. For example, the fluoranthene reservoir in the lake sediment is about two orders of magnitude larger than that for PFOS. For fluoranthene, removal via sedimentation could already be found in the reed belt of the Wulka. Also, for the rest of the reed belt there is clear evidence for a removal of fluoranthene from the open lake via sedimentation of suspended matter. This situation also indicates a potential release from the reservoir in the reed belt into the lake, 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.

2.5 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 is formed in the lake by precipitation and other processes, it is only a matter of time until the relatively shallow lake basin is filled up – unless the input is significantly reduced and/or the discharge or removal is forced. This concerns the aspect of sedimentation in the literal sense, quasi a "filling" of the lake basin by solids (see Figure 19 right). To be distinguished from this is 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 19 middle).

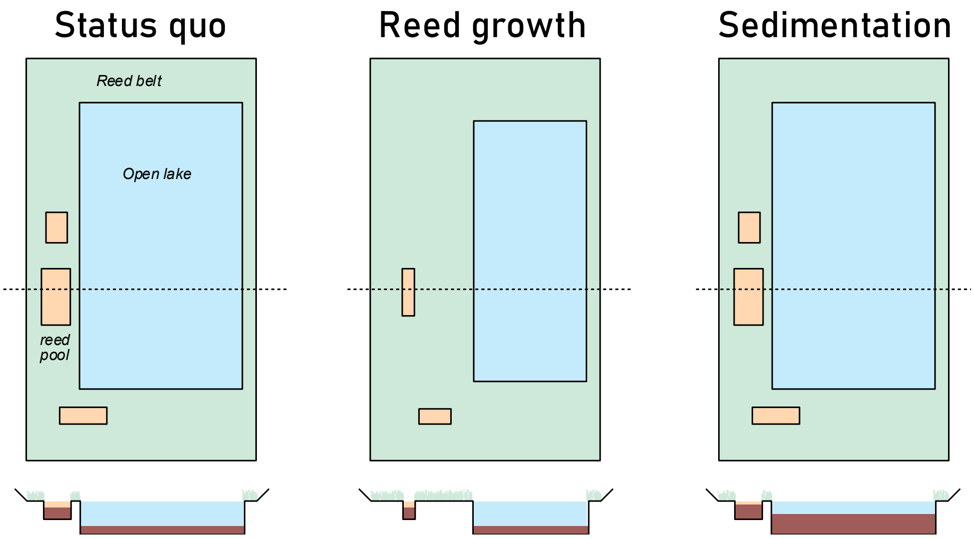

Figure 19. Schematic drawing of "Verlandung" in the sense of an increase of reed stands (middle) and of sedimentation (right).

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 the water management objectives which address sedimentation and reed growth.

A second long-term aspect already mentioned in Report 1 "Hydrology" is **global warming**. The investigations of Soja *et al.* (2014) show a noticeable shortening of periods with ice cover of the lake within the last 100 years (Figure 20), while Dokulil (2013) showed a significant temperature increase of the lake over the last few decades (Figure 21). 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.

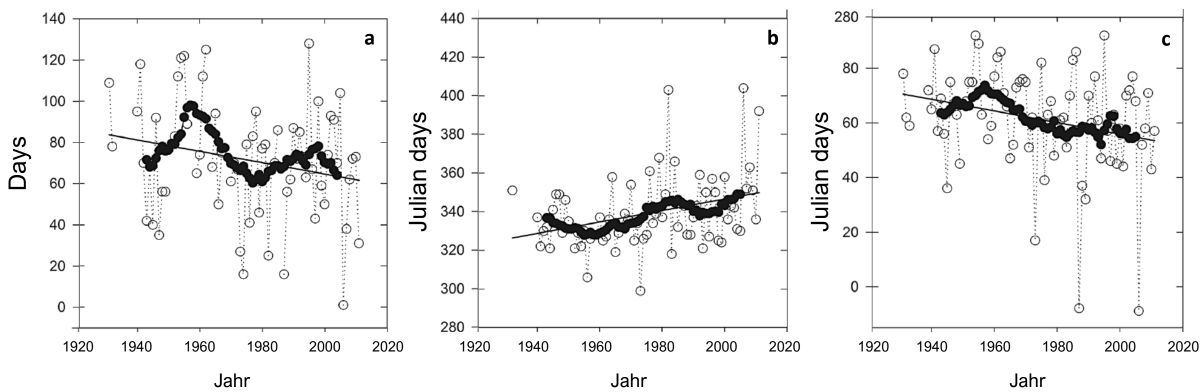

Figure 20. Change of the duration (a), the start (b) and the end (c) of ice cover in Lake Neusiedl during the last 100 years (from: Soja *et al.* (2014)).

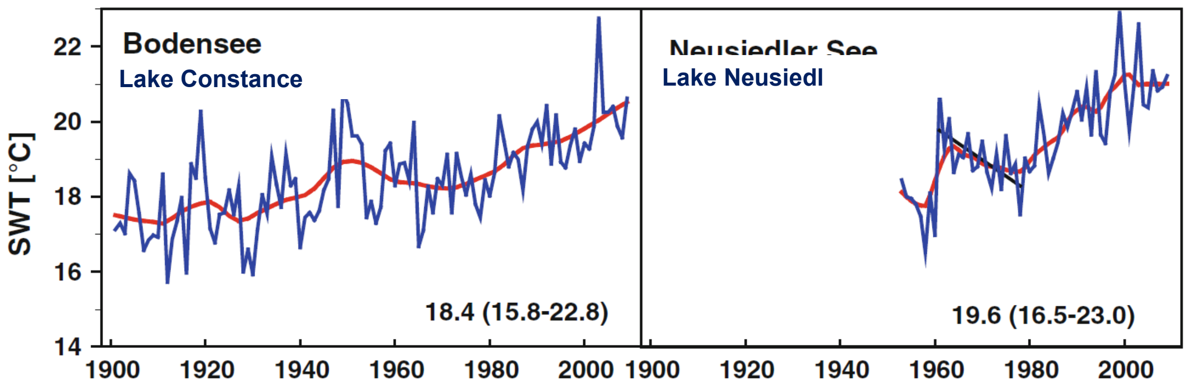

Figure 21. Increase of summer surface water temperature (SWT) of the deepest and the most shallow lake in Austria over the last decades (from: Dokulil (2013)).

As discussed in Report 1 "Hydrology", 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.

A gradual increase in the concentration of water constituents is to be expected as water levels decrease, as it was also shown by modelling the salt content for long dry periods. The climate modelling in Gabriel *et al.* (2012) and the mass balance based on it (Wolfram *et al.* 2012) predict 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 discharge to the Hanság Channel, such values can 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. In the Hungarian part of Lake Neusiedl, an increased penetration of the littoral bulrush (*Schoenoplectus litoralis*) has occurred in recent years – possibly a consequence of global warming and the first trends towards changes in Lake Neusiedl (see Dokulil (2013)).

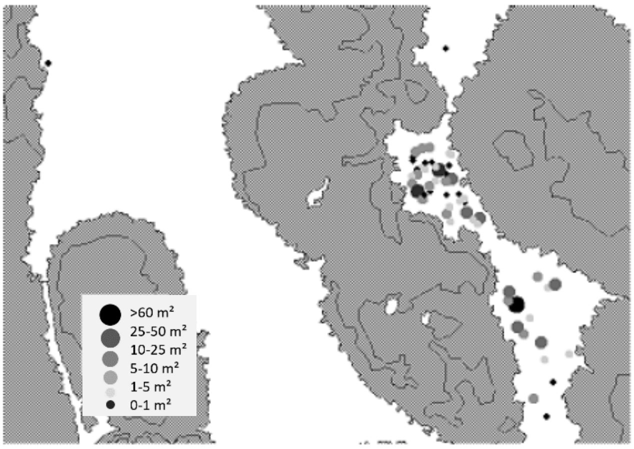

Figure 22. Distribution of the littoral bulrush *(Schoenoplectus litoralis)* in the southern part of the Bay of Fertőrákos (source: M. Pannonhalmi).

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

3 SCENARIOS – DIFFERENT FRAMEWORK CONDITIONS

3.1 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 2.2 & 2.3 the water level (and thus indirectly the climatic and meteorological conditions) and the structure of the reed belt (and here primarily the reed channels) were described as the most important factors for material transport. Therefore, it seems reasonable to define scenarios based on these two factors. Thereby three pairs of scenarios are distinguished.

3.1.1 Scenarios "Extreme water levels"

In the investigation period within the framework of the project REBEN, the water level of Lake Neusiedl varied between 115.3 and 115.6 m asl (max. 115.5 m 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 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 the effects of high water level are considered, but no measures taken to reach this level (*e.g.* external water supply). Consequences however are considered (outflow over the Hanság Channel).

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

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

3.1.3 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 the channels, but also the connected retention area behind. Here, four types of reed structure can be roughly distinguished. Almost half of the Austrian reed belt is very dense (type A) and at the 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 monitoring station IL9 at Illmitz Seebad, 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 23).

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

- **Scenario S1** No channels or existing channels 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 23)

- **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)

Like scenario W2, S2 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 outside the National Park, as no anthropogenic interventions are currently permitted in the conservation zone in the southern part of the lake. This also means, however, that there will always be areas in the entire Lake Neusiedl / Fertő that are not connected to the open lake, even in scenario S2.

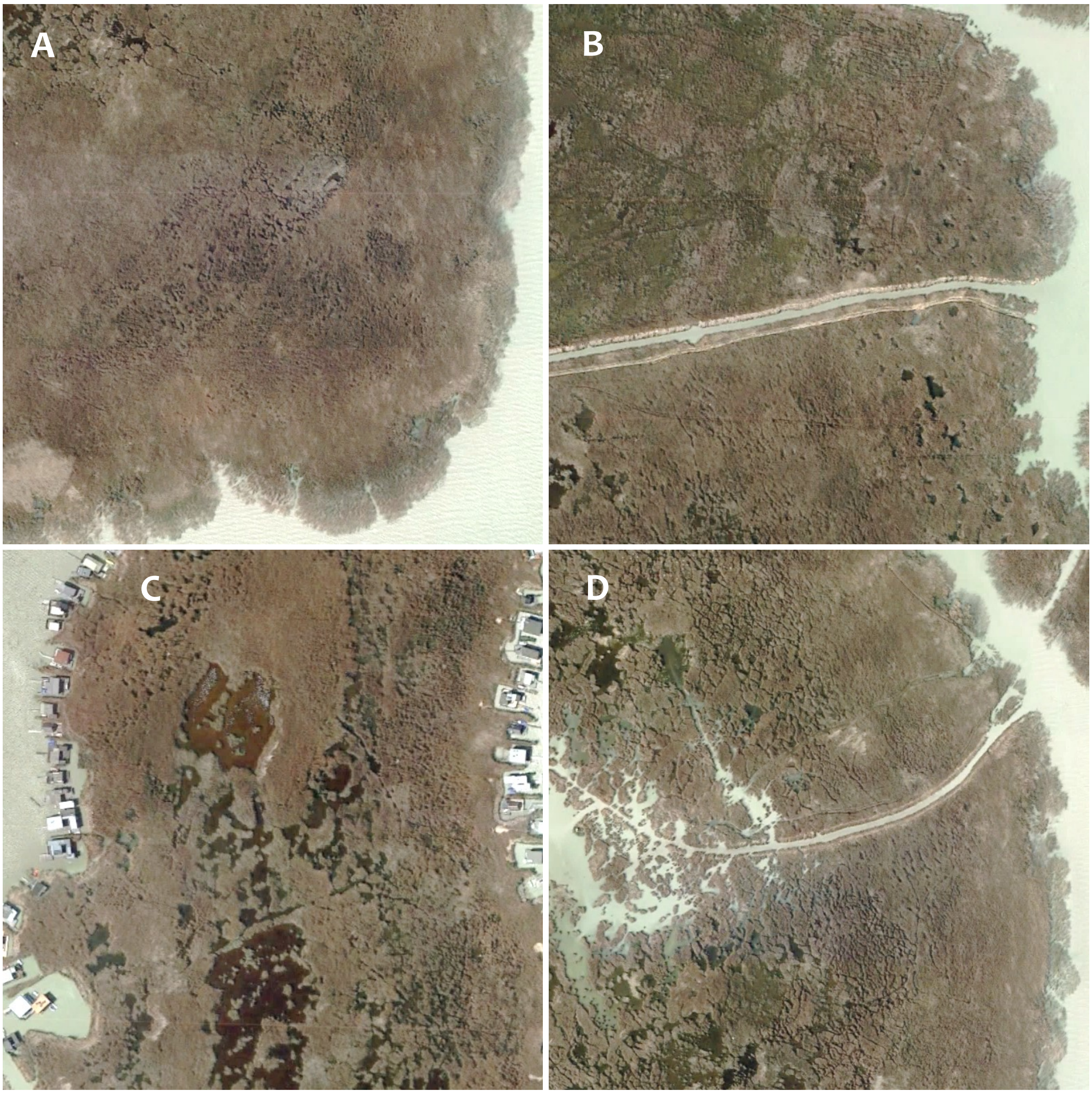

Figure 23. Different characteristics of the reed belt near Oggau/Rust. A: area with dense reed without pools and channels, B: area crossed by a channel without lateral connection, C: area with pools without connection to the lake, D: area with pools with good connection to the lake.

For these six scenarios, the gradients, exchange processes and loads shown in Chapter 2 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) or the load estimates derived from them (Chapter 2.4 of the present report).

3.2 Scenario P1 – Water level <115.2 m ü.A.

The scenario with a water level <115.2 m asl is not purely hypothetical, even though the 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 transported 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 stronger seiche movements and waves to be able to introduce water into the channel (Figure 24).

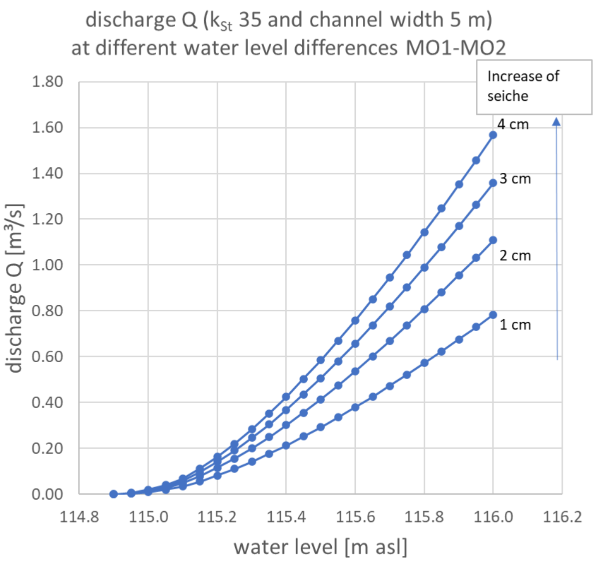

Figure 24. Relation between water level and discharge through a channel near Mörbisch assuming varying water level differences (MO1 lake edge, MO2 reed belt) resulting from a seiche wave (applying the Manning-Strickler formula).

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 on 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 (increased?) degradation of organic material. However, this assumption cannot be based on any findings or reliable evidence at present.

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 increased 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 (Table 5). These 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 rate of 0.18 mm. If the sediment volume is related to an estimated 10 km^2 of bays and wind-protected areas, *i.e.* potential deposition zones, the rate increases accordingly to almost 2 mm/a, *i.e.* a few centimetres in 10 years.

Also for nutrients, a significantly lower 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 phase. Impacts on the concentration of other substances are described in Chapter 2.5.

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, an increase in the enrichment factor *(af)* and thus higher concentrations in the lake than at present must be considered.

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 as compared to today can be expected, even if the level of release and thus internal loading of the lake (*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 case 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 the solids into the reed belt, the data for lead and other heavy metals indicate that adsorption in the reed belt currently also outweighs the release 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 25. 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 are shown in different colours (orange ... increasing, green ... decreasing, grey ... constant).

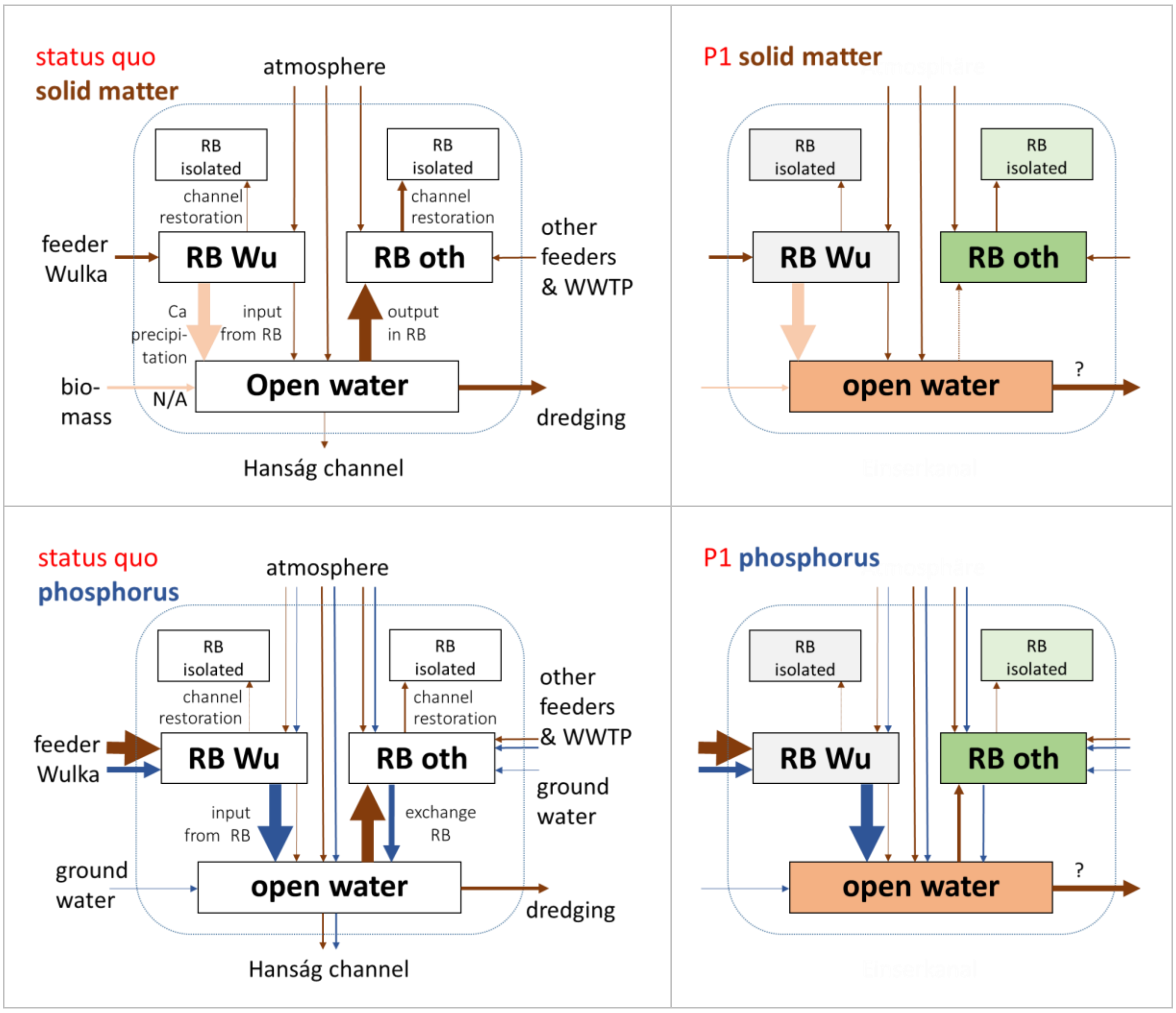

Figure 25. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario P1.

3.3 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 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 discharge 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 effective water exchange between the open lake and the reed belt (see Figure 24). It can also be expected that the "range" of the waves and seiche movements is wider than at medium water level. A small part of the water loads into the reed belt will be diffuse, at least in the areas 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 an 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"). 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 keep 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).

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 cause 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 can affect the basic chemism of Lake Neusiedl. According to the current weir operation regulations, from November to January, from a water level of 115.70 m asl up to 15 m³/s are discharged via the Hanság Channel, from April to August up to 6 m³/s. In the months in between, the limit water level shifts gradually; the limit for the discharge is 6 m³/s in February and March, and 15 m³/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 26).

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 26. Flood situation at the bathing resort of Illmitz on 9^{th} 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 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 per year – taking into account the figures and assumptions regarding water content and density as stated in the Report 2 "Reeds". 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 shown in Figure 27. For explanation of the symbols see scenario P1.

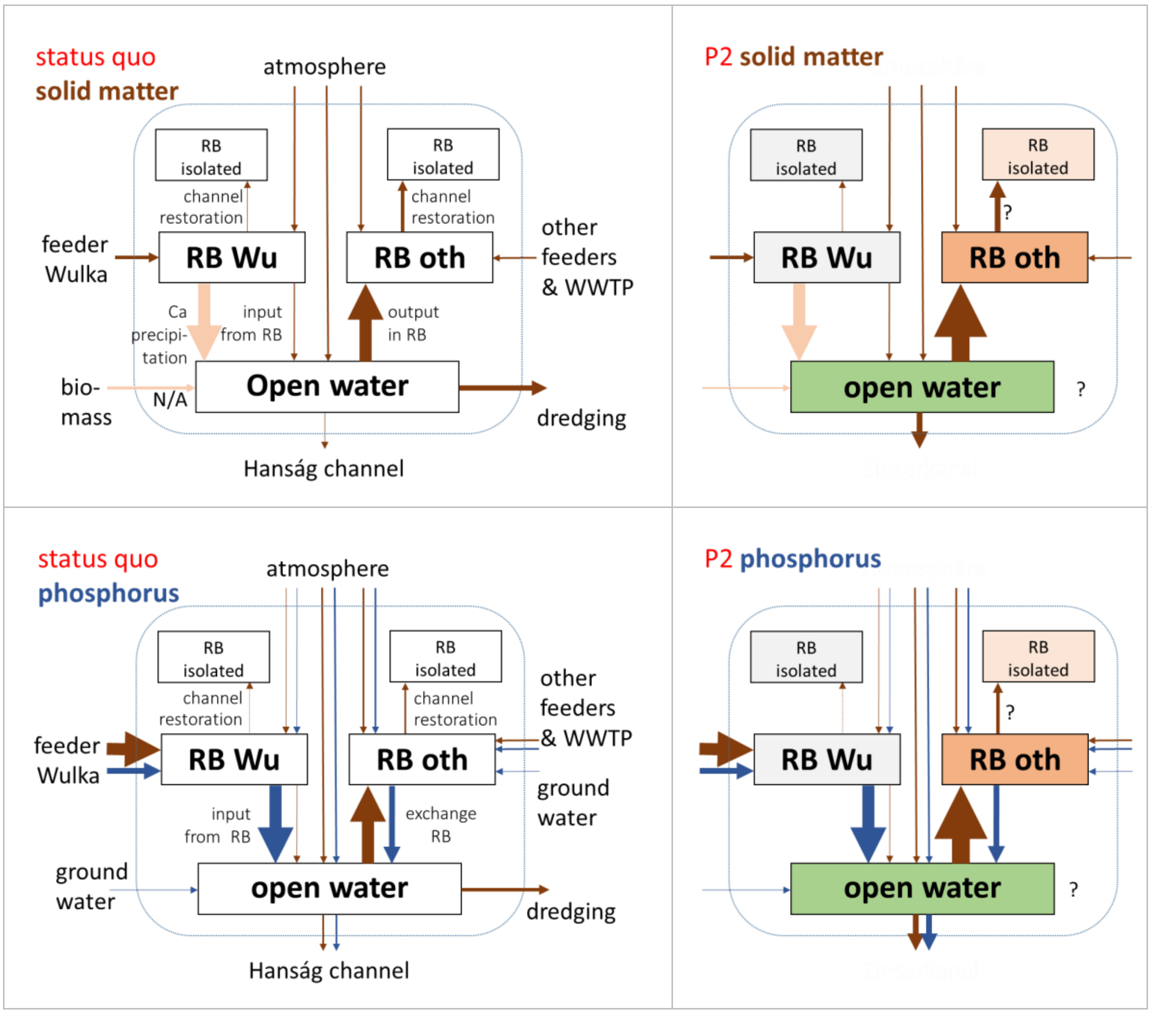

Figure 27. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario P2.

3.4 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 field 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 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 will no longer be maintained and that even a low water discharge will 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 5, 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) settles in the reed belt of the Wulka. However, a tendential increase of the retained load is likely. Here, the question inevitably arises as to how long will a deposition of an average of about 3 800 t of solid matter per year (as dry matter, corresponding to about 10 000 m³ of wet volume) in the Wulka estuary be possible in view of the increasing silting-up. Related to a reed belt of about 10 km², 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 Report 3 "Chemistry": data from the sampling site WU3). Based on 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 below 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 release plays a negligible role.

It is assumed that this scenario would have no significant impact on the pollution of the lake and thus on the risk of failing to meet the EQS. Largely persistent substances that are predominantly transported in dissolved form (*e.g.* PFOS or PFOA) are likely to pass the reed belt of the Wulka unaffected, as in the case of this scenario. For predominantly particle-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 solids retention is expected. In the case of metals such as lead, a similar behaviour to that of phosphorus can currently be observed. A retention of particulate lead is opposed by a release 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 valuable hotspot for ecology and nature conservation. 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 28.

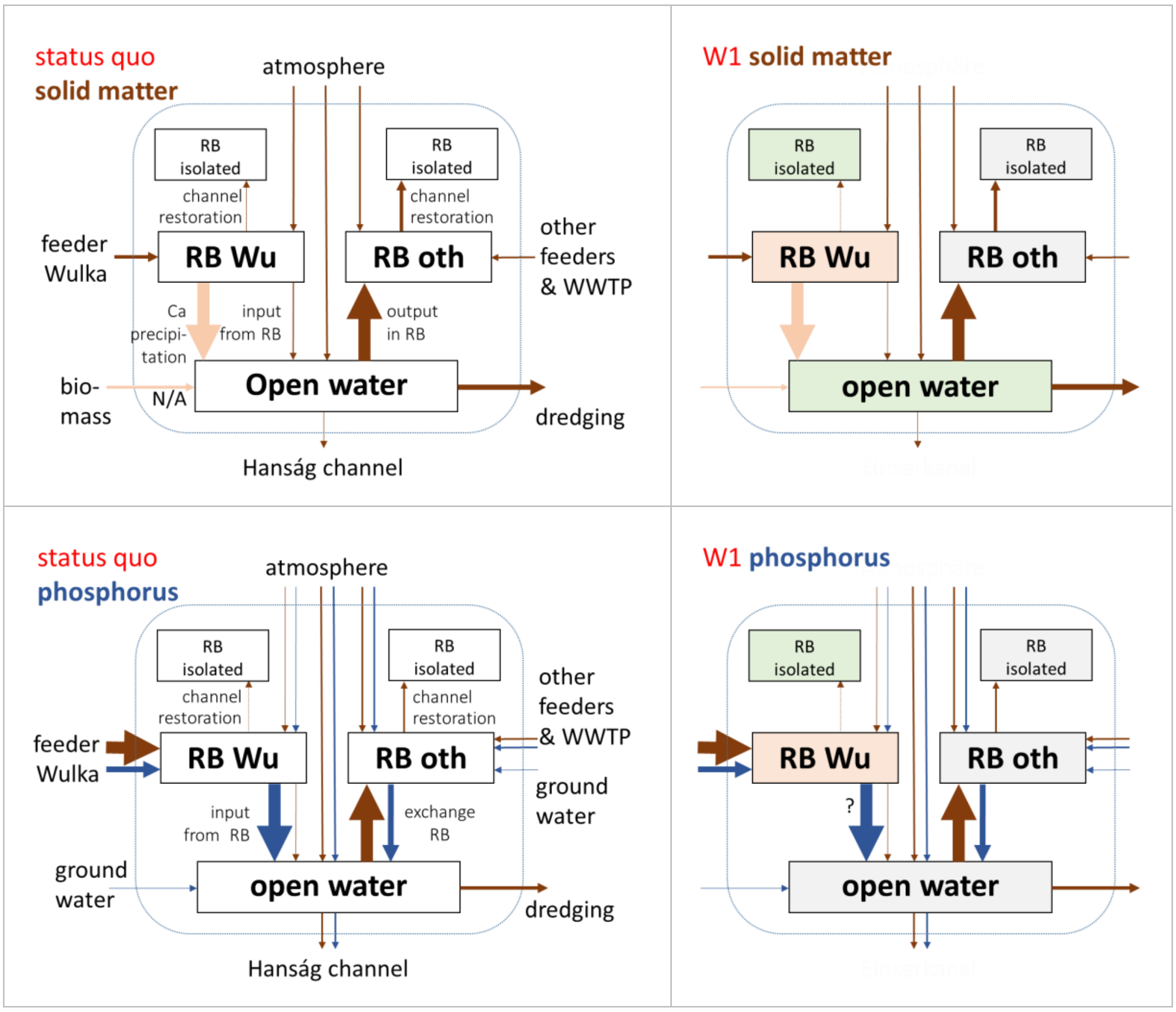

Figure 28. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario W1.

3.5 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 for 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 to 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) is 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 feasible, 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 particles (silt to sand) would probably be deposited to a large extent in the north of the lake, the finer particles 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 might not be 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 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 loading 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 respective 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 & Mikschi 2007, 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 29.

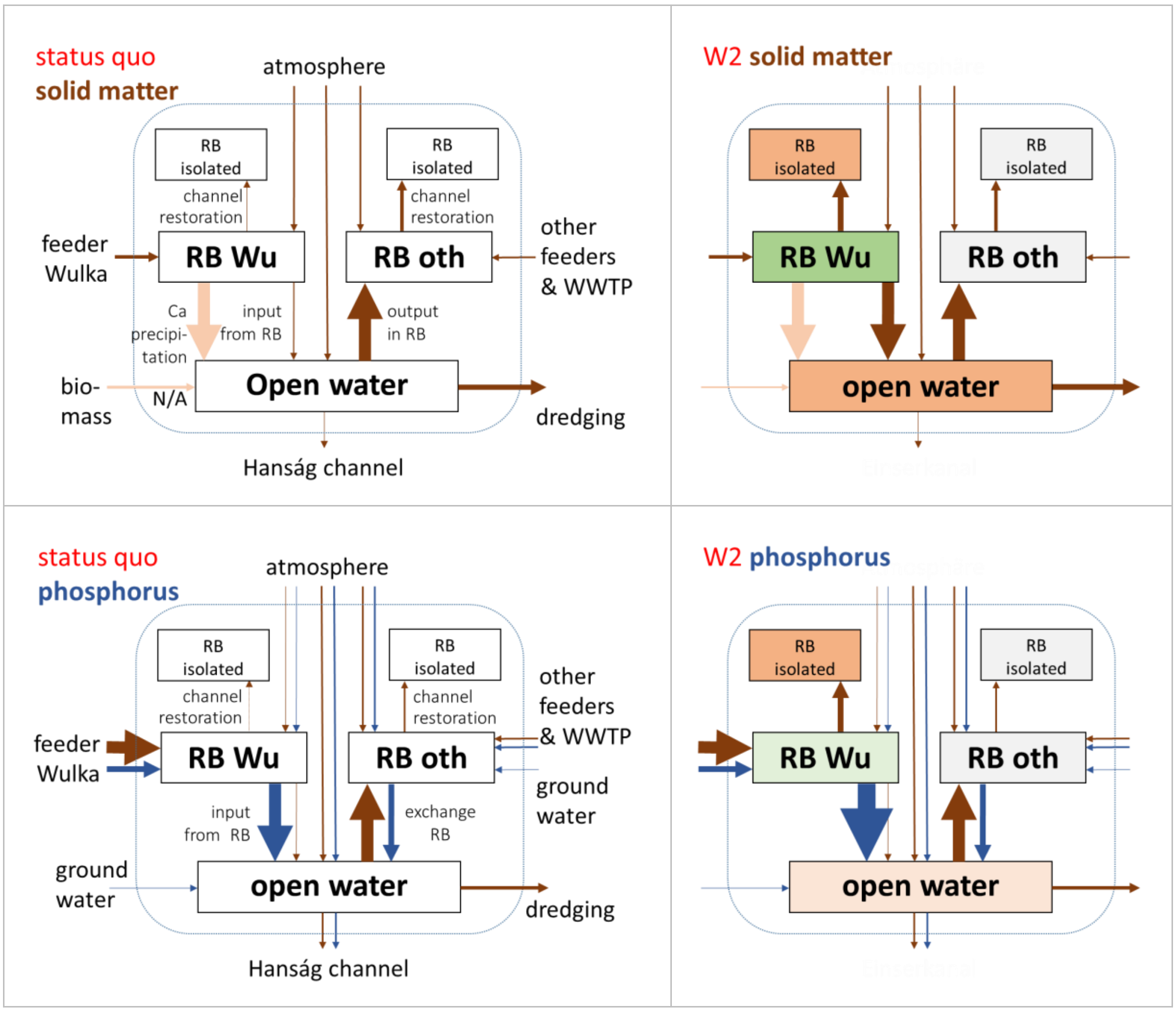

Figure 29. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario W2.

3.6 Scenario S1 – no reed channels

Our knowledge about the water exchange between the open lake and the reed belt, in 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 varied 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 in a series of measurements in the fall of 2019 ("wind event", see Report 5) 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 were 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 exchange lake – reed belt 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 is transported into the inner reed belt at all. But even at medium water levels above the top 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. Already south of the road to the marina of Illmitz there is 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 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 14). 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 with particles is initially deposited as such but can be released again in dissolved form via biological cycles. Both in dissolved and 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 cause 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 between the open lake and 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 lake. Nevertheless, the risk of missing 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 30.

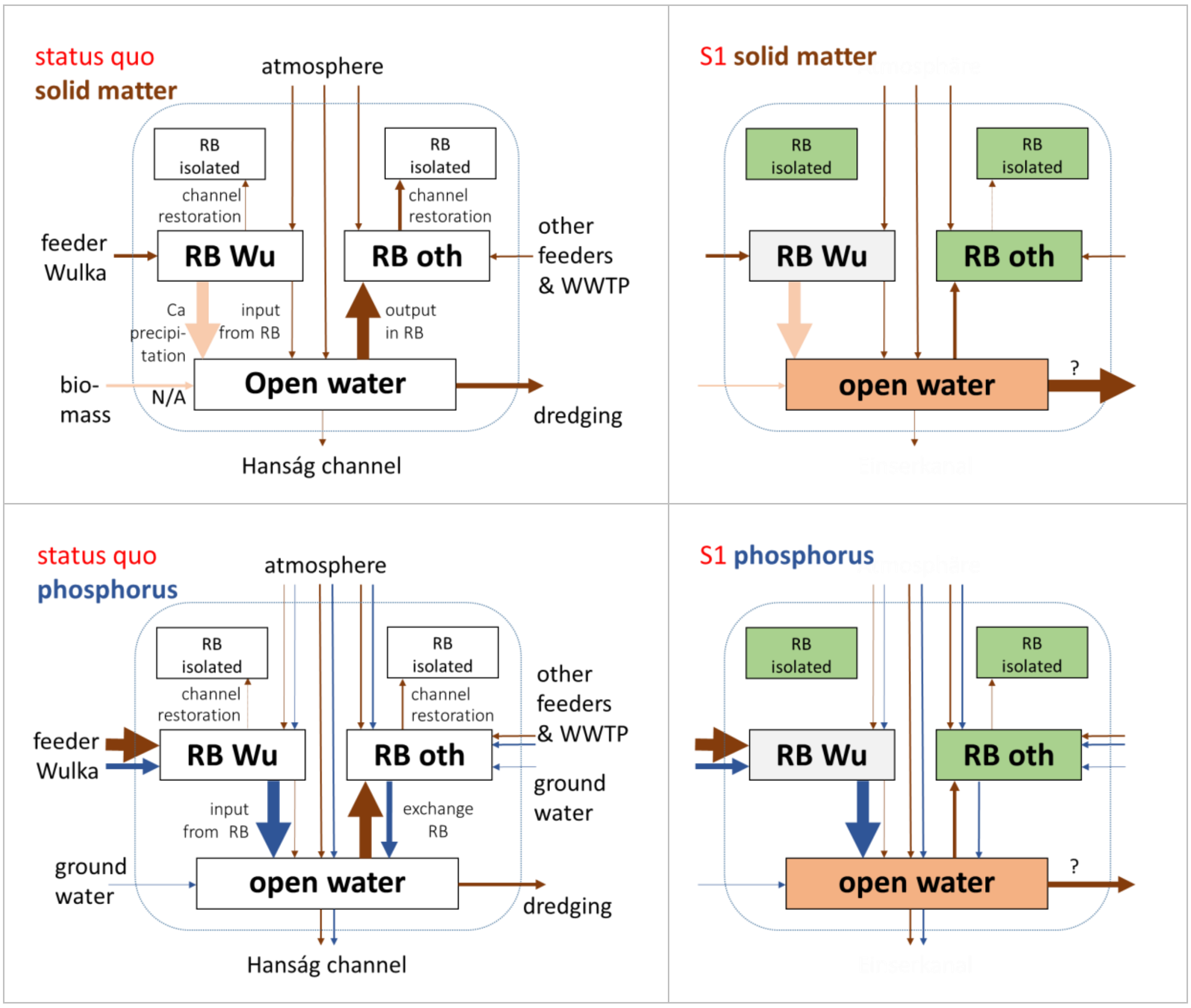

Figure 30. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario S1.

3.7 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 regularly been maintained in the last years (see Report 2 “Reed”). 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[3].

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[4].

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 31). 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”), 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 32 – 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

[3] 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.

[4] 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 conditions.

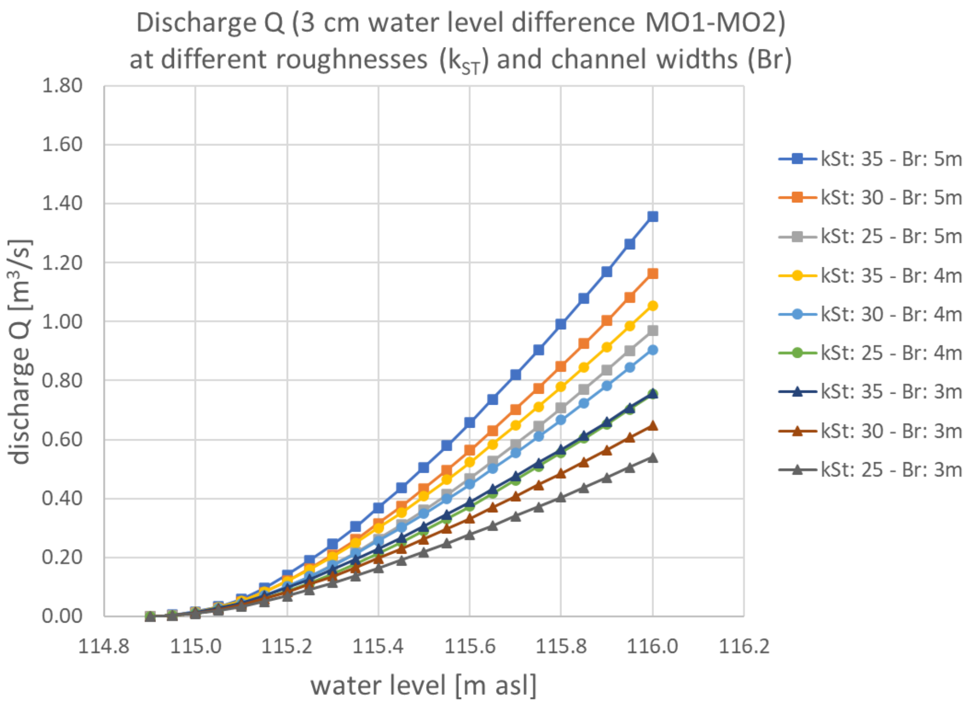

Figure 31. Relation between water level and discharge through a channel near Mörbisch assuming varying channel width, using the Manning-Strickler formula (MO1 lake edge, MO2 reed belt).

Figure 32. Reed channels with varying width. Left: near Fertőrákos (Hungary), right: near Mörbisch (Austria). Photos: M. Pannonhalmi (left), G. Kum / DWS Hydro-Ökologie (right).

A key question in this scenario 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 when*. A comparison of different orthophoto images from the reed belt gives an indication. Figure 33 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 33. Comparison of the reed belt near Mörbisch in the 1990ies (top left), in spring 2012 (top right) and 2020 (bottom left). Source: 1990ies Biological Station Illmitz, 2012 & 2012: 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: a 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 it 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 a sedimentation basin, which was built for intermediate storage 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 could obviously not recover. Today the area presents itself as a water surface with rare reed stands and thus as a potential sedimentation area, which it 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.

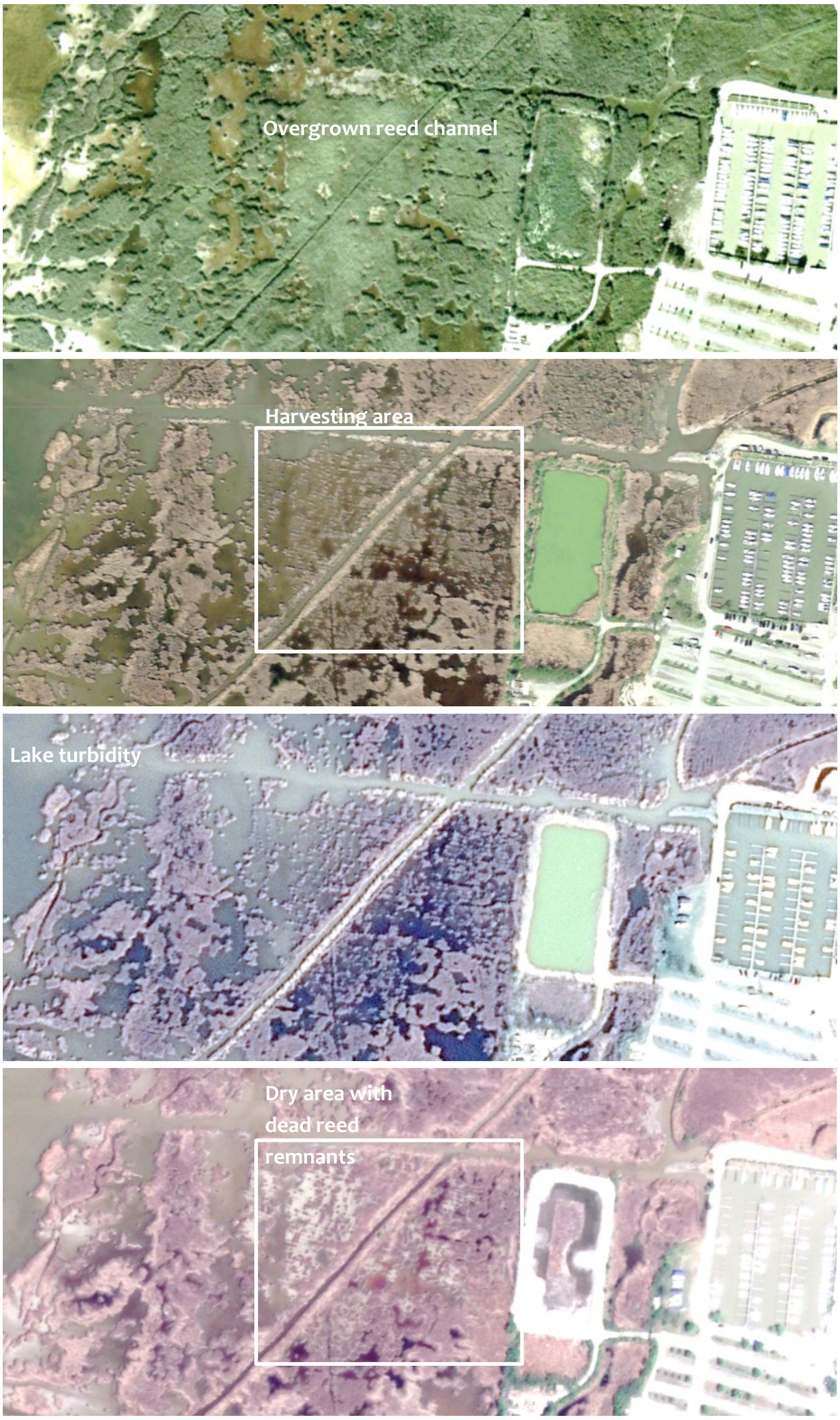

Figure 34. Changes of the structure of the reed belt in a small area near Mörbisch resulting from reed harvesting (source: Google Earth).

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 deposition of the 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 Reports 3 and 5) and must be taken into consideration. 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, if effects on the water balance are neglected, an increased concentration of pollutants would have no negative effect 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 would be required.

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.

Finally, the considerations are presented in Figure 35, again with regard to effects on the overall balance for solids and phosphorus.

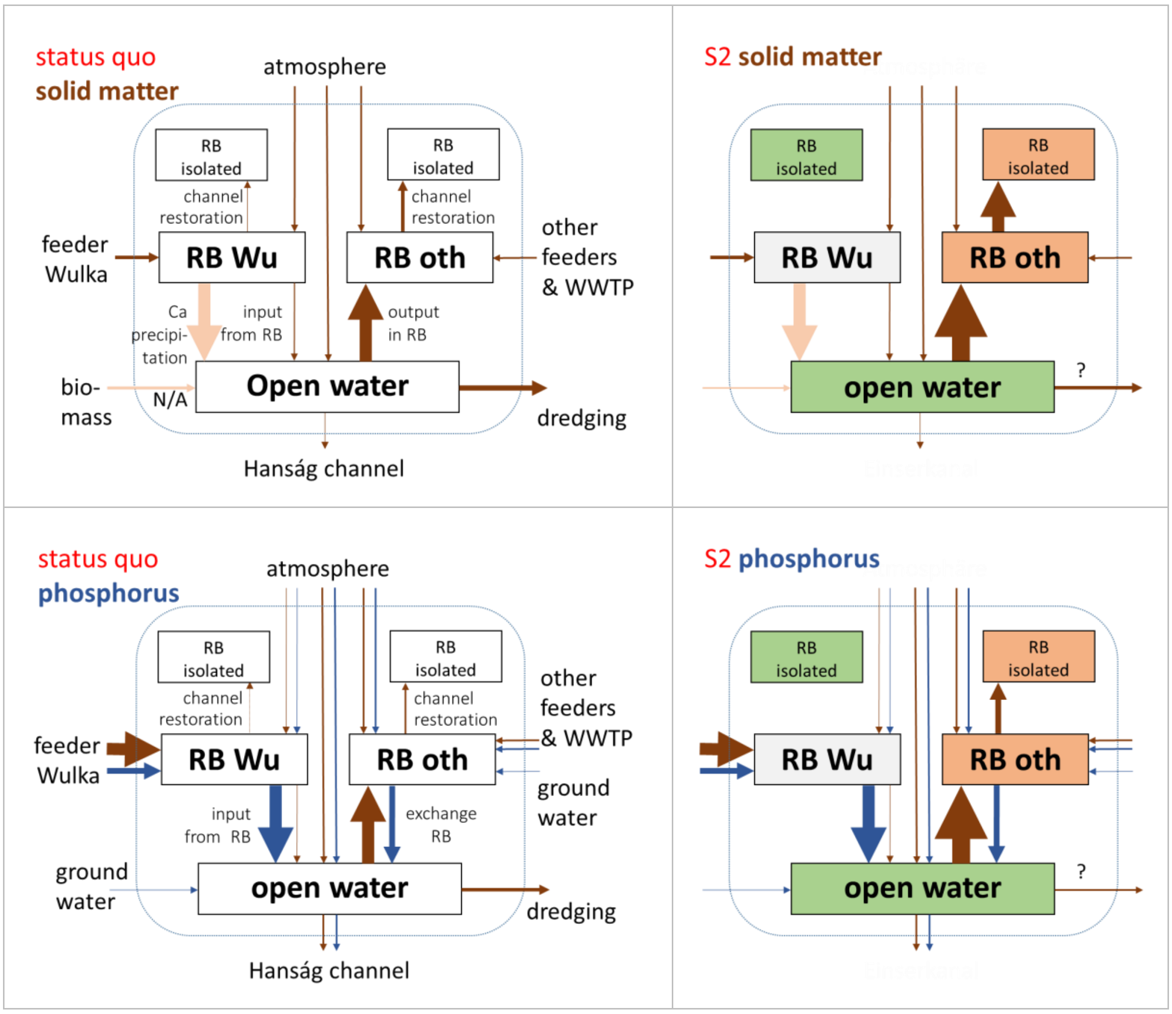

Figure 35. Alteration of matter flows for sediment (upper) and phosphorus (lower) in scenario S2.

3.8 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 a.s.l.). 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 keeping at least partially 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**, lower (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 loads 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 crucial 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 upgrading) 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.

As explained above, the six scenarios basically consist of three opposing pairs. In combination, these scenarios can lead to increase or 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 complex 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. They were not defined on the basis of the expected development of Lake Neusiedl 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 would develop in the next 20 years without human intervention.

This inevitably leads to a thematic field that has been addressed in Report 1 "Hydrology" as well as further above in Chapter 2.5: the effects of **global warming** on Lake Neusiedl. 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 a.s.l.) 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) or through changes in the existing water level regulation or an external water supply.

4 ASSESSMENT

This chapter summarizes the results of the scenario descriptions and compares them with the most important water management objectives defined in Chapter 1.3 according to the Strategy Study Neusiedler See (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 to reed" occurs twice in the objectives of the Lake Neusiedl Strategy Study, 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 the field of hydro-morphology according to the Strategic Study Lake Neusiedl ("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 19 right). Likewise, the objective "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 Lake Neusiedl Strategy Study 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 19 middle).

In the following, the six scenarios are evaluated according to the objectives as defined in the Strategy Study Lake Neusiedl. 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. This is first 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 the reed channels and the water level, or other 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 addresses 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 approach 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 Lake Neusiedl Strategy Study, but it seems reasonable to add this point to the list of goals – although even after the GeNeSee project it is 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 prevention of 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 enhanced water exchange between 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 the estuary area is affected . 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 and 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*).

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 Lake Neusiedl Strategy Study 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 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 might no longer resemble the diverse habitat that this part of Lake Neusiedl 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 ecosystem" for a long time *(weak evidence)*.

Further objectives address the **natural development** of Lake Neusiedl. 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 channels, dredging at the lake shore). In parts, the lake can develop undisturbed today, but only within the limits set with measures for over 100 years and under the burden of impacts of past decades. The objectives for natural development can be understood in a way 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.* when the currently endorheic lake is transformed into a "flow-through" water body, it is hardly possible to speak of an **undisturbed course of the 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, it therefore seems justified (or maybe even necessary) to support the biological processes with moderate measures such as maintaining a certain degree of exchange, as well as 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 way and extent 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 brings a deterioration or a higher 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 release of substances 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 predominantly linear flow of the Wulka through the reed belt 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 as a result of the sediment management is open.

The following Table 7 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 7. 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 hydromorphological 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 ecosystem	=	=	na	na	=	=
Phys.-chem. Parameters	Preservation of natural chemistry	++	– –	=	=	=	=
	Preservation of natural physico-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)[5]	– –	++	=	–	– –	++
Biology	Preservation of good ecological status (biology)[6]	+	–	–	+	–	+
	Preservation of natural variability (biodiversity, abundance and productivity)	+	–	+	–	±	±
	Biological processes should run largely undisturbed	+	– –	+	–	±	±

[5] *sensu* Qualitätszielverordnung Chemie Oberflächengewässer (BGBl. II Nr. 96/2006 idgF)
[6] *sensu* Qualitätszielverordnung Ökologie Oberflächengewässer (BGBl. II Nr. 99/2010 idgF)

5 KNOWLEDGE DEFICITS AND OPEN QUESTIONS

In 2014, Wolfram et al. (2014) summarized the current state of knowledge in various specialist areas in the Lake Neusiedl Strategy Study 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 Lake Neusiedl region.

One of these knowledge deficits concerns the water and material exchange between the open lake and the reed belt – a complex of processes 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. This area was already addressed by the GeNeSee project. 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 on the edge between reed and lake and on the open water areas in the reeds (Csaplovics & Schmidt 2011a; Csaplovics & Schmidt 2011b), they allowed creating a digital terrain model for these three areas that could be used for hydraulic modelling.

A comprehensive **survey of the sediment levels** in the reed belt, especially in the area of the sea 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 an external water supply to Lake Neusiedl.

(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 inorganic 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**.

(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)

From biota investigations in Lake Neusiedl it is known that the EQS for mercury and PBDE are not met. This is not a specific feature of Lake Neusiedl, as the target is not met throughout Austria and large parts of the EU. The parameters of the

Qualitätszielverordnung Chemie Oberflächengewässer (QZV Chemie OG, BGBl. II Nr. 96/2006, a national regulation of immission limits for chemicals in surface water) in Lake Neusiedl have not been monitored so far, because the national monitoring program according to the Gewässerzustandsüberwachungsverordnung (GZÜV, BGBl. II Nr. 479/2006, a national monitoring regulation) does not include a monitoring point in Lake Neusiedl. The present investigations within 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.

(5) 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 potential long-term mobilization (see above), for other parameters this must be attributed to a degradation or conversion under the specific environmental conditions of the lake (*e.g.* carbamazebine, 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 perflourized 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.

6 LITERATURE

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