

Effects of reduced load in the River Danube on nutrients and phytoplankton dynamics in the flood-relief channel New Danube (Vienna, Austria)

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With 11 figures in the text

Abstract: Spatio-temporal distributions of plant nutrient concentrations, turbidity, chlorophyll-a and phytoplankton biomass are evaluated for a 10-year dataset from both impoundments of the New Danube flood-relief channel at Vienna, including measurements from the main River Danube. Concentrations of phosphorus primarily are influenced by groundwater transfer of water and nutrients from the main river into the two impoundments, percolating through the gravel substratum of a newly constructed island separating the Danube from the New Danube. Variations of phosphorus input in turn affect the amounts of chlorophyll-a and phytoplankton developing in the impoundments. In the Danube, turbidity depends mainly on discharge, but in the New Danube, although influenced by wind and wave action, turbidity is basically associated with direct inputs from the river when flood-gates are opened. When the channel was first filled with water, all variables had concentration gradients down its 21-km length. Over time, trophic levels have fallen considerably, from hypertrophic to oligo-mesotrophic, with a concurrent reduction of phytoplankton biomass. Species composition of algae has changed to a lesser extent.

Introduction

In some respects the New Danube is a relatively unique water body. Designed and constructed primarily to prevent the city of Vienna from flooding by the River Danube, after construction in the 1980s the two narrow (ca. 200 m wide) but long (21 km overall) upper and lower impoundments of the flood-relief channel rapidly became a recreational attraction for local citizens, because there is easy access, 42 km of shoreline and reasonable water quality. For most of the year the impoundments are supplied by groundwater which percolates through the gravel of the newly constructed, narrow Danube Island which separates the New Danube from the River Danube flowing alongside (HUMPESCH et al. 2000).

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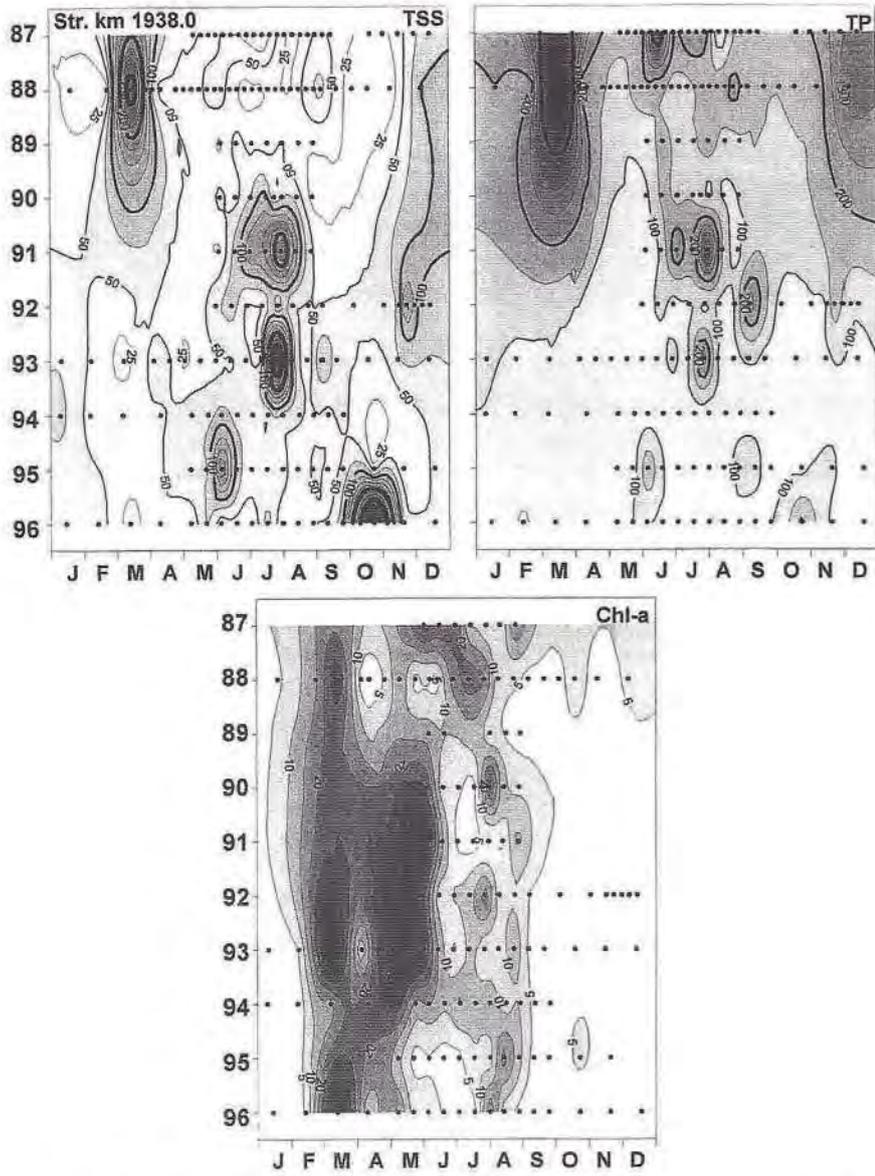


Fig. 1. Contour plots for years versus months in the period 1987–1996 for the River Danube at stream-km 1938.0. Top left: Total suspended solids (TSS) in mg l^{-1} . Top right: Total phosphorus (TP) in $\mu\text{g l}^{-1}$. Bottom centre: Chlorophyll-a (Chl-a) in $\mu\text{g l}^{-1}$. Dots indicate the sampling schedule.

Even so, the functional dynamics of this unusual freshwater ecosystem are also of general interest, because elsewhere many floodplain lakes lying close to the banks of rivers also receive most of their water from groundwaters seeping through the hyporheic zone (VANEK 1987, 1991; GILBERT et al. 1990; ŠMILAUER et al. 1996). Similar situations are found in water bodies along river dams (e.g. NACHTNEBEL 1989; WALKER et al. 1992).

This study focuses on the causes and consequences of nutrient input by groundwater seepage and floods, and their effects on nutrient dynamics and phytoplankton changes associated with long-term reduction in nutrient loading from the River Danube.

Material and methods

The results presented here cover the 10-year period from 1987 to 1996. Throughout this period, samples were taken at several locations and time intervals differing from year to year. Sampling frequency each year is indicated by the sampling dots shown in Fig. 1. All samples were surface samples taken from either the right or left bank, because cross-sectional and depth gradients proved to be random and statistically were not significant (DOKULIL & TEUBNER 1999).

All chemical analyses follow standard methods (MACKERETH et al. 1989). Chlorophyll-a was estimated spectrophotometrically from hot ethanol extracts, modifying the technique proposed by NUSCH (1980). Abundance and biomass of phytoplankton was assessed using the inverted microscope technique (UTERMÖHL 1958). Counting was performed with the plankton enumeration program, version 3.1B, by HAMILTON (1990). Biomass was calculated from size measurements using the image analysis system LUCIA V 3.51a, Lab. Imag. Ltd., interfaced to a NIKON Diaphot inverted microscope.

Contour plots of time resolution (years vs. months) were created by KRIGING with modified search radius to allow for abrupt data changes using SURFER 5.0 (Golden Software Inc.). The goodness of fit is exemplified for the adopted interpolation strategy, using phytoplankton biomass data from km 21.1 (Fig. 8, bottom panel).

Seasons are averaged according to: spring = March–May, summer = June–August, autumn = September–November, winter = December–February. Data were transformed and standardized for principal component analyses (PCA) of limnological parameters and phytoplankton composition using the computer program STATGRAPHICS plus 2.0 (STSC Inc., USA).

Triangular diagrams (Fig. 6) showing the relation between the three main macroelements – nitrogen, phosphorus and silica – were created in GRAPHER 4.0 (Golden Software, Inc.). To show the relative availability of these plant nutrients, concentrations of total nitrogen (TN), total phosphorus (TP) and the soluble fraction of silicon (SRSi) are considered here. In contrast to the conservative element silicon which is recycled at longer intervals (SOMMER 1988; BARKER et al. 1994), phosphorus and nitrogen are rapidly recycled. Moreover, these two elements may be stored intracellularly (e.g. in polyphosphate bodies and cyanophycin granules). Therefore, the total concentrations are better estimators of the nutrient pool for algal growth than the dissolved fractions of either phosphorus or nitrogen (compare THOMPSON & RHEE 1994).

For clearer presentation of the points within the areas available on the diagrams (Fig. 6), the concentrations were normalized by relating the concentration of each element to its sum over the entire dataset:

$$(C_{\text{norm}} = \frac{100 C}{\sum_{i=1}^n C_i}, \sum_{i=1}^n \text{TN}_i = 47.68 \text{ mg l}^{-1}, \sum_{i=1}^n \text{TP} = 1.13 \text{ mg l}^{-1}, \sum_{i=1}^n \text{SRSi}_i = 42.99 \text{ mg l}^{-1})$$

The normalization is based on the entire dataset for three years (1988, 1995 and 1996), but for clarity the results are shown in three displays (Fig. 6A–C). The intersection point of the three lines (a, b, and c in Fig. 6) shows the molar optimum ratio of TN:TP:SRSi = 16:1:17. The lines indicate the constant ratios of TN:TP = 16:1 for variable SRSi (a), SRSi:TN = 17:16 for variable TP (b), and SRSi:TP = 17:1 for variable TN (c). For further explanation, normalization and calculation of lines for constant ratios, refer to TEUBNER (1996) and TEUBNER et al. (2000).

Results

In the River Danube, concentrations of total phosphorus (TP) declined continuously from 1987 to 1996 (Fig. 1, top right panel). Values over $200 \mu\text{g l}^{-1}$ are associated with large amounts of total suspended solids (TSS) during floods (Fig. 1, top left panel). Higher loads of suspended matter in March 1988, July/August 1991 (a 100-year flood) and July 1993, are clearly manifested in the TP contours (Fig. 1). From 1992 onwards, concentrations of TP fall below $100 \mu\text{g l}^{-1}$ for most of the year. Higher values are only observed occasionally, again linked to higher values of TSS. Chlorophyll-a (Chl-a) in the river exceeds $20 \mu\text{g l}^{-1}$ in the first half of each year, successively declining to less than $5 \mu\text{g l}^{-1}$ thereafter. Highest concentrations are observed in March and May, particularly in 1993.

Plant nutrients enter the New Danube by groundwater seeping through the aquifer of the narrow island separating it from the River Danube. Although chemically altered and largely precipitated (KREUZINGER & MATSCHÉ 2000), concentrations of both TP and total soluble phosphorus (TSP) in the New Danube correlate significantly with those in the main river (Fig. 2).

Within the two impoundments of the flood-relief channel, TSS concentrations are patchy throughout the seasons at all stations, but higher values usually occur during autumn and winter (Fig. 3). Amounts decrease markedly from north (upper end) to south (lower end), but do not show a tendency to reduce over time. During the period of maximum discharge in the 100-year flood in July/August 1991, and during the opening of the channel's flood-gates in March 1988, high river levels and flows caused turbidity and TP concentrations to increase dramatically (Figs. 3 and 4). Similarly, two floods in March and (especially) October 1996 appear in the graphs of TSS at all sampling stations (Fig. 3), while elevated TP values also show up more distinctly in October (Fig. 4). Concentrations of TP were not sufficiently high in March to be represented in the contour plots.

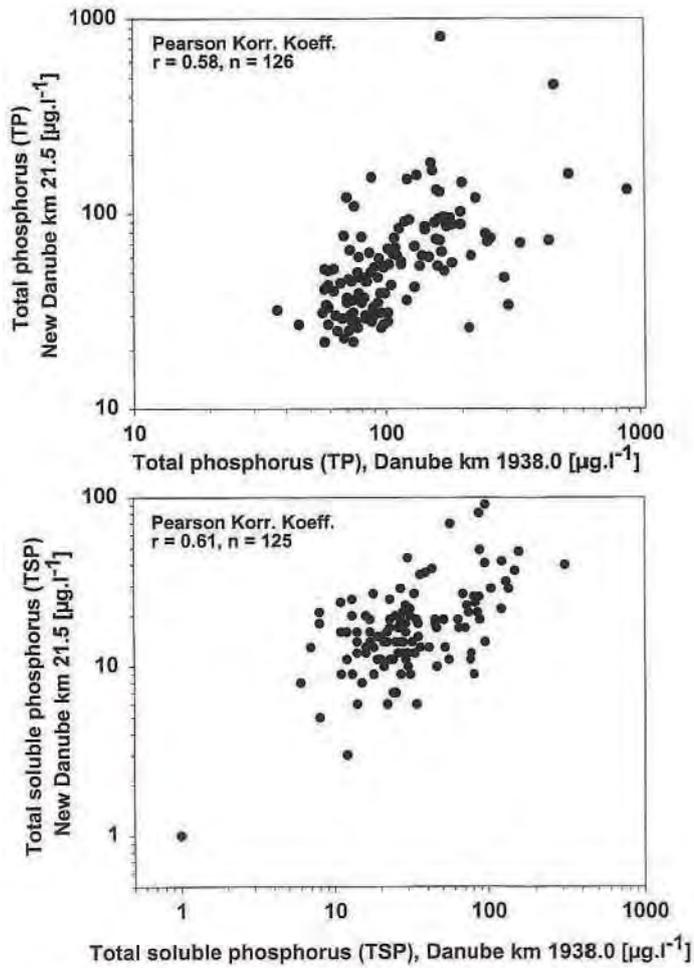


Fig. 2. Scatter plot of total phosphorus (TP) in the River Danube at km 1938.0 versus TP in the New Danube at km 21.1 (top panel), and total soluble phosphorus (TSP) at both locations (bottom panel). All values are in $\mu\text{g}\cdot\text{l}^{-1}$.

Total phosphorus in the New Danube decreases over time from 1987 to 1996, corresponding with a reduction of TP in the main river and along the 21-km stretch of the channel. Values above 50 or even $100\ \mu\text{g}\cdot\text{l}^{-1}$ are typical for the upper impoundment in years prior to about 1992. In later years, such concentrations occur only during floods. Total nitrogen concentrations (not shown here) range from $< 1\ \text{mg}\cdot\text{l}^{-1}$ to $> 4\ \text{mg}\cdot\text{l}^{-1}$, with no significant trend of a reduction over time.

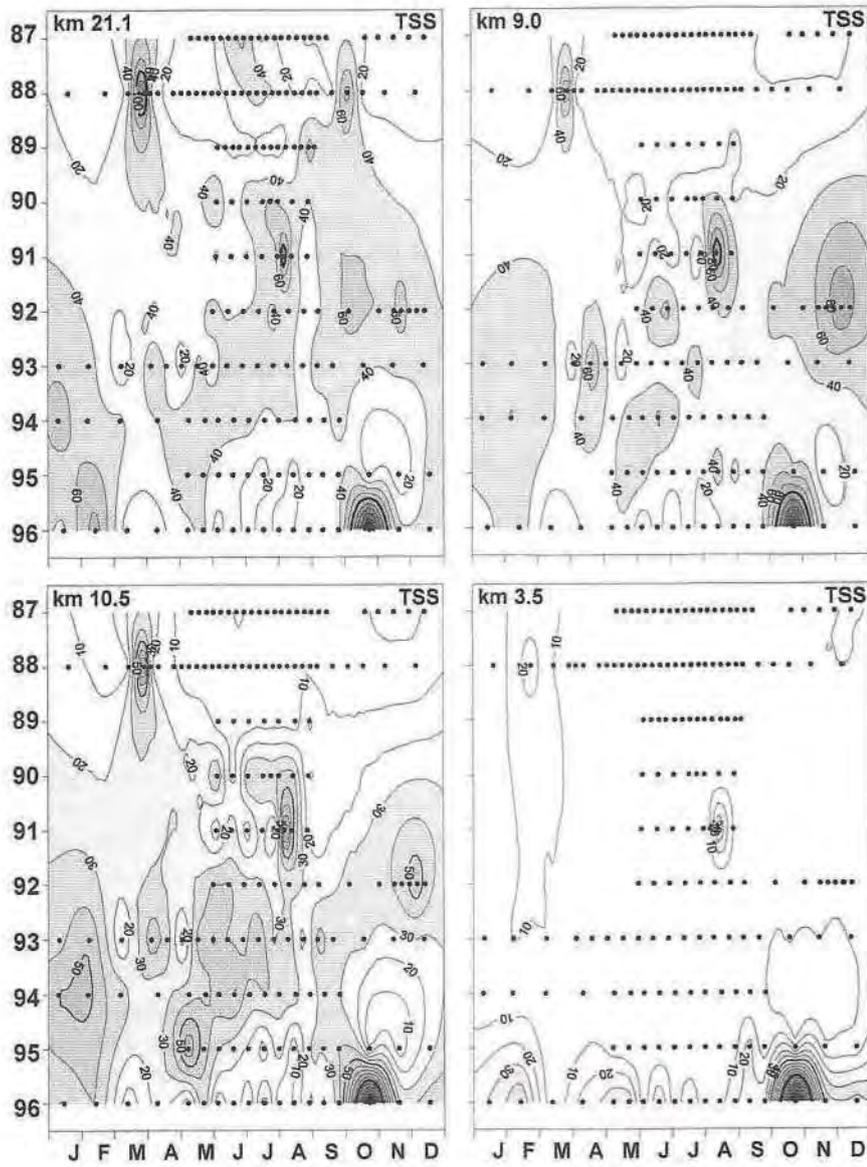


Fig. 3. Contour plots for years versus months in the period 1987–1996 for total suspended solids (TSS, mg l^{-1}) in the New Danube at km 21.1 and km 10.5 in the upper impoundment, and at km 9.0 and km 3.5 in the lower impoundment. Dots indicate the sampling schedule.

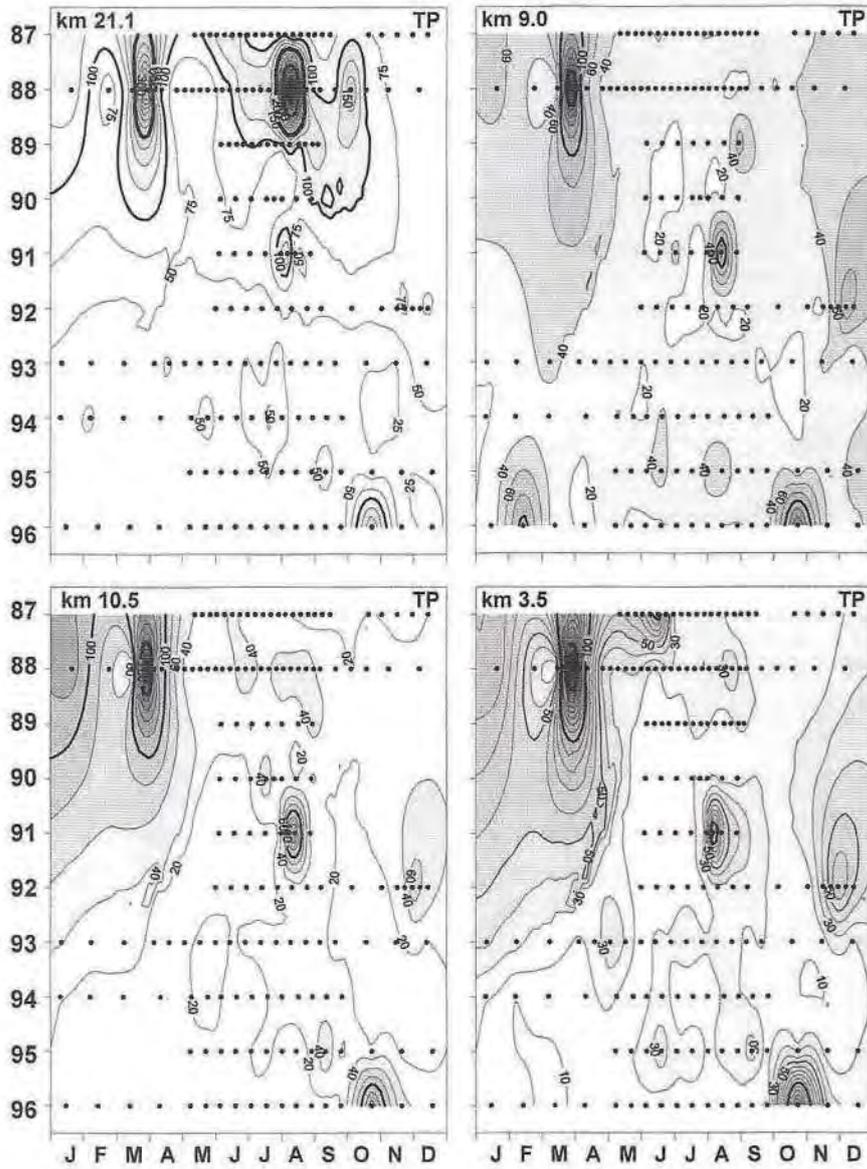


Fig. 4. Contour plots as in Fig. 3, for total phosphorus (TP, $\mu\text{g l}^{-1}$).

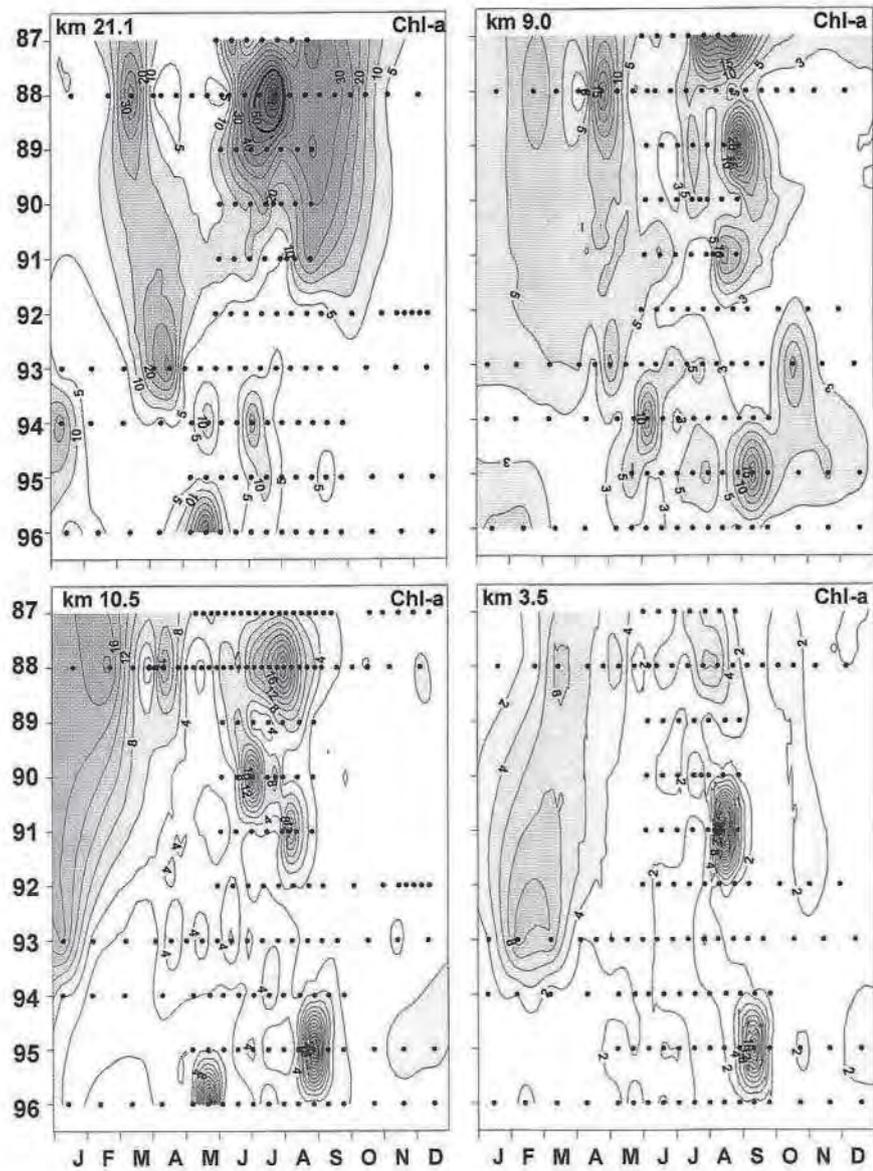


Fig. 5. Contour plots as in Fig. 3, for chlorophyll-a (Chl-a, $\mu\text{g l}^{-1}$).

As an indicator of phytoplankton biomass, Chl-a (Fig. 5) largely resembles the distribution of TP. Concentrations much greater than 10–20 $\mu\text{g l}^{-1}$ occur in spring and summer of the first four years of the observation period. Values during autumn and winter are usually below 5 $\mu\text{g l}^{-1}$. Short-lived pulses of P-input by flooding are followed by short-lived concentration increases of Chl-a at all stations (e.g. early August 1991, March 1996). An overall gradient of decreasing Chl-a concentrations from north to south (i.e. from km 21.1 to km 3.5) is detectable in all plots, with less Chl-a in the lower impoundment except for 1995, where elevated concentrations occur in September (Fig. 5). Like TP, the general trend of Chl-a concentrations over time is towards more moderate values below 5 $\mu\text{g l}^{-1}$.

Relationships between TN, TP and SRSi at all sites and between investigated years (1988, 1995 and 1996) do not vary markedly (Fig. 6). The lack of points on the right-hand side of line A in Fig. 6 indicates that seasonal averaged TN:TP ratios are always much above the optimum molar ratio of 16:1. The arrangement of points below the line SRSi:TN = 17:16 (line B in Fig. 6), but not below the line SRSi:TP = 17:1 (line C), shows that in all three years the average seasonal concentrations are at low ratios of SRSi:TN and high ratios of SRSi:TP at the same time. The optimum ratio of TN:TP:SRSi = 16:1:17 is never achieved; points do not coincide with the intersection of lines A, B, and C.

An increasing variability of seasonal TN:TP ratios, from 1988 to 1996, is indicated in Fig. 6. The enlargement of the range encountered is due to the long-term reduction of TP levels at highly seasonal – but not interannual – fluctuating concentrations of TN.

The relationships between twelve limnological variables are shown in Fig. 7. The PCA vectors for organic, inorganic and total suspended solids, and TP, lie close together, indicating that inorganic and organic solids are loaded in a more or less constant ratio: the concentrations of TP increase at higher loads of suspended solids (compare Figs. 3 and 4). Thus TP is closely coupled to the suspended solids while available-P (i.e. $\text{PO}_4\text{-P}$) is inversely related to Chl-a, as are nitrate (NO_3) and silicate (SRSi).

The PCA vectors for Chl-a, pH and temperature also lie close together. The largest concentrations of Chl-a therefore occur at high temperatures in summer, when concentrations of available nutrients are at low levels. However, the development of algal biomass (determined as Chl-a) and concentrations of soluble nutrients are largely independent from the loading of suspended solids, as indicated by the triangular arrangement of the PCA vectors for Chl-a, a group for $\text{NO}_3 + \text{SRSi} + \text{PO}_4$, and a third group for suspended solids (Fig. 7). The seasonal TN concentrations are closely related to NO_3 but independent from TP. Seasonal changes in conductivity do not influence the development of Chl-a and soluble nutrient concentrations.

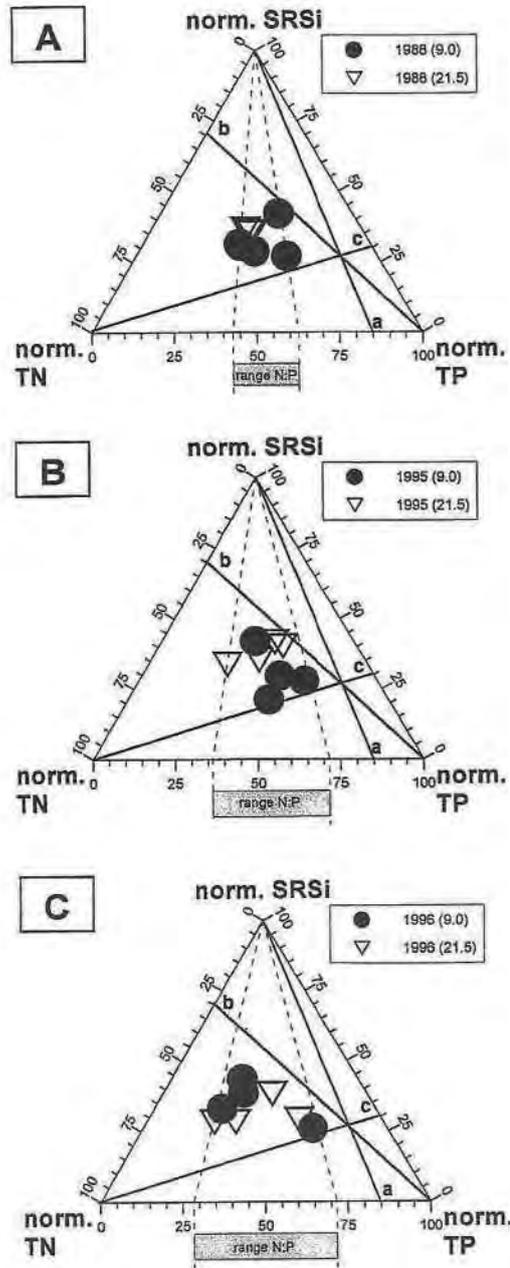


Fig. 6. Triangular diagrams of normalized nutrient element ratios for 1988, 1995 and 1996 (TN_{norm}:TP_{norm}:SRSi_{norm}). The lines (a, b, c) indicate constant optimum ratios of two elements at variable concentrations of the third element (for details refer to Methods). The dashed lines and the bar "range of N:P" show the variation of this ratio.

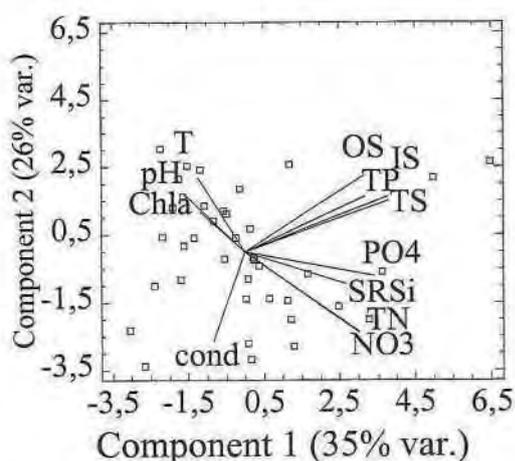


Fig. 7. Biplot of the first versus second principal component for twelve limnological variables (vectors) and distribution pattern of the seasonal averaged water samples (points) in 1995–96. Abbreviations: temperature (T), conductivity (cond), concentration of chlorophyll-a (Chl-a), soluble reactive silicon (SRSi), nitrate–nitrogen (TN), orthophosphate–phosphorus (PO₄), total phosphorus (TP), inorganic solids (IS), organic solids (OS), and total solids (TS).

Phytoplankton biomass data, which have been sampled and analysed less frequently, closely resemble Chl-a concentrations at km 21.1 in the upper impoundment (Fig. 8, top left panel), with the exception of October 1995 when small Cyanobacteria low in chlorophyll content were dominant (Fig. 9, top left panel). In the lower impoundment, at km 9.0, results for phytoplankton biomass are available from 1992 onwards, and again these largely confirm results from chlorophyll analyses (Fig. 8, top right panel). At km 21.1 phytoplankton biomass was high in 1988. The three major peaks in March–April, June–July and September–October (Fig. 8, top left and bottom panel) exceed $10,000 \mu\text{g l}^{-1}$ fresh weight (max. $24,000 \mu\text{g l}^{-1}$). The spring period is dominated by a mixture of diatoms (Bacillariophyceae, Fig. 9, top right panel). The summer season starts with conspicuous green-algal development, declining thereafter into early autumn (Fig. 9, bottom left panel). Chrysophyceae and Cryptophyceae are co-dominating groups in late summer and early autumn (Fig. 9, top and bottom centre panels). Finally, Cyanobacteria and dinoflagellates co-dominate in the September–October development, accompanied by diatoms (Fig. 9, top left and bottom right panel).

A somewhat similar pattern is repeated at a much lower level of biomass (average ca. $700 \mu\text{g l}^{-1}$ fresh weight) in the years 1992 to 1996. Diatoms are present in small amounts all year round, peaking in spring and occasionally during summer after flooding (e.g. August 1991), and producing maxima in the

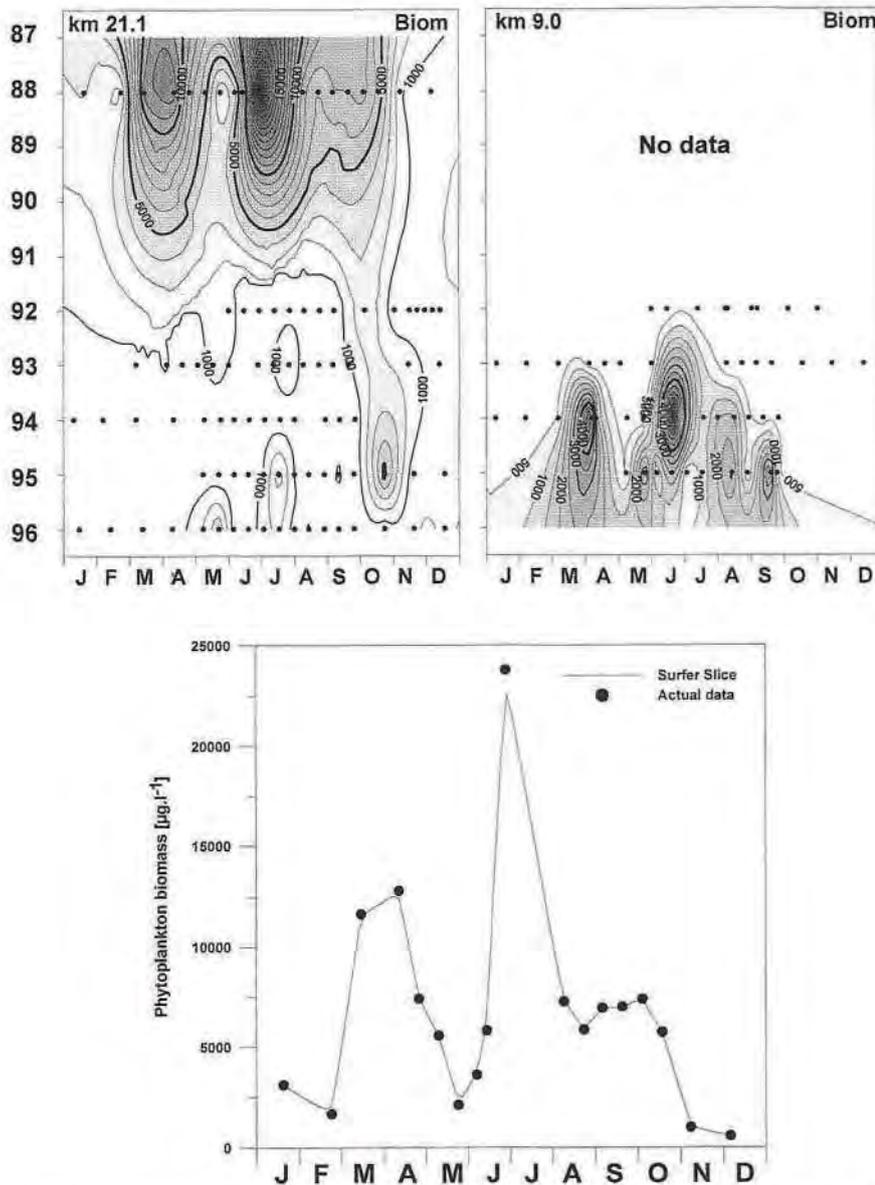


Fig. 8. Contour plot of total phytoplankton biomass (Biom, $\mu\text{g l}^{-1}$) at km 21.1 in the New Danube (top left) and at km 9.0 (top right). Bottom centre: Goodness of fit for the contours obtained by surfer slice (see Methods) and actual data-points obtained for phytoplankton biovolume in 1988 (taken from the top left contour plot).

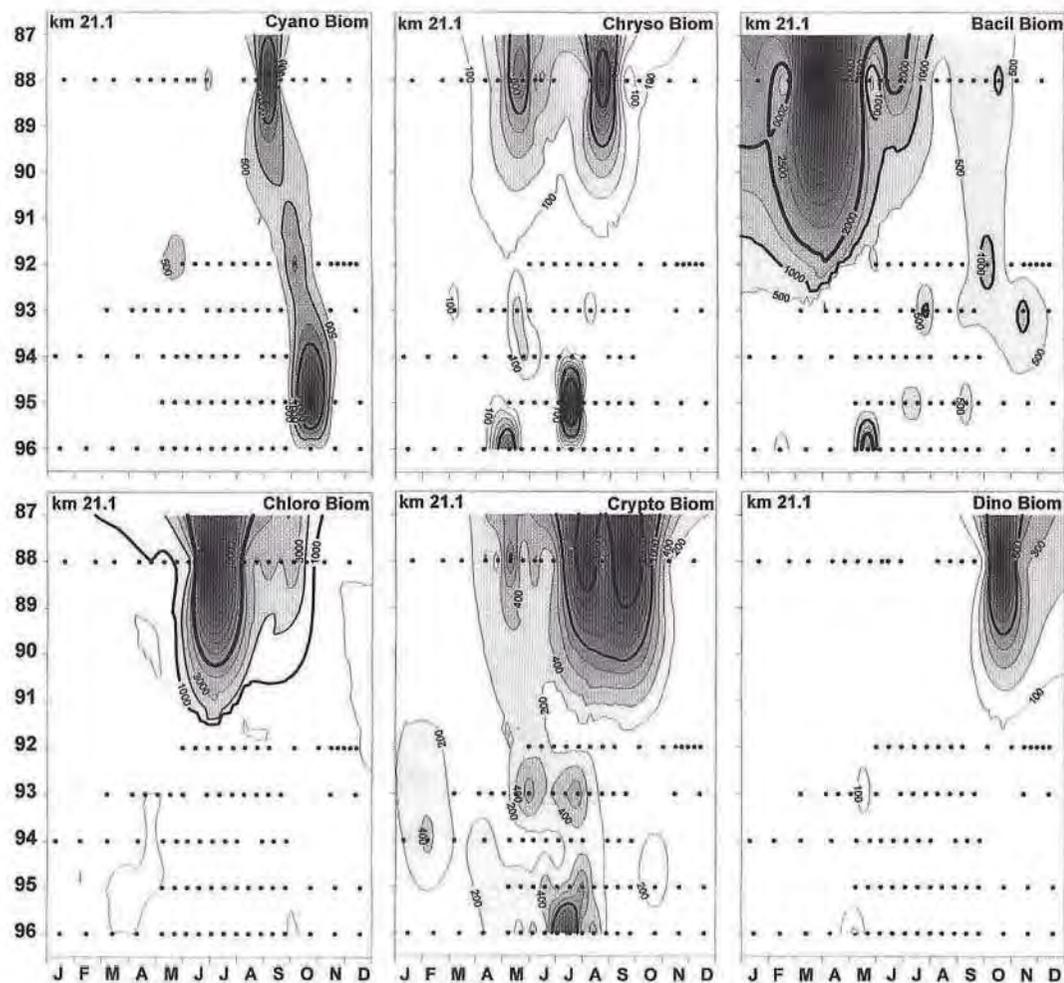


Fig. 9. Contour plots for the biomass of individual phytoplankton algal groups at km 21.1 in the New Danube. All in $\mu\text{g FW l}^{-1}$. From top left to bottom right: Cyanobacteria (Cyano Biom), Chrysophyceae (Chryso Biom), Bacillariophyceae (Bacil Biom), Chlorophyceae (Chloro Biom), Cryptophyceae (Crypto Biom) and Dinoflagellates (Dino Biom).

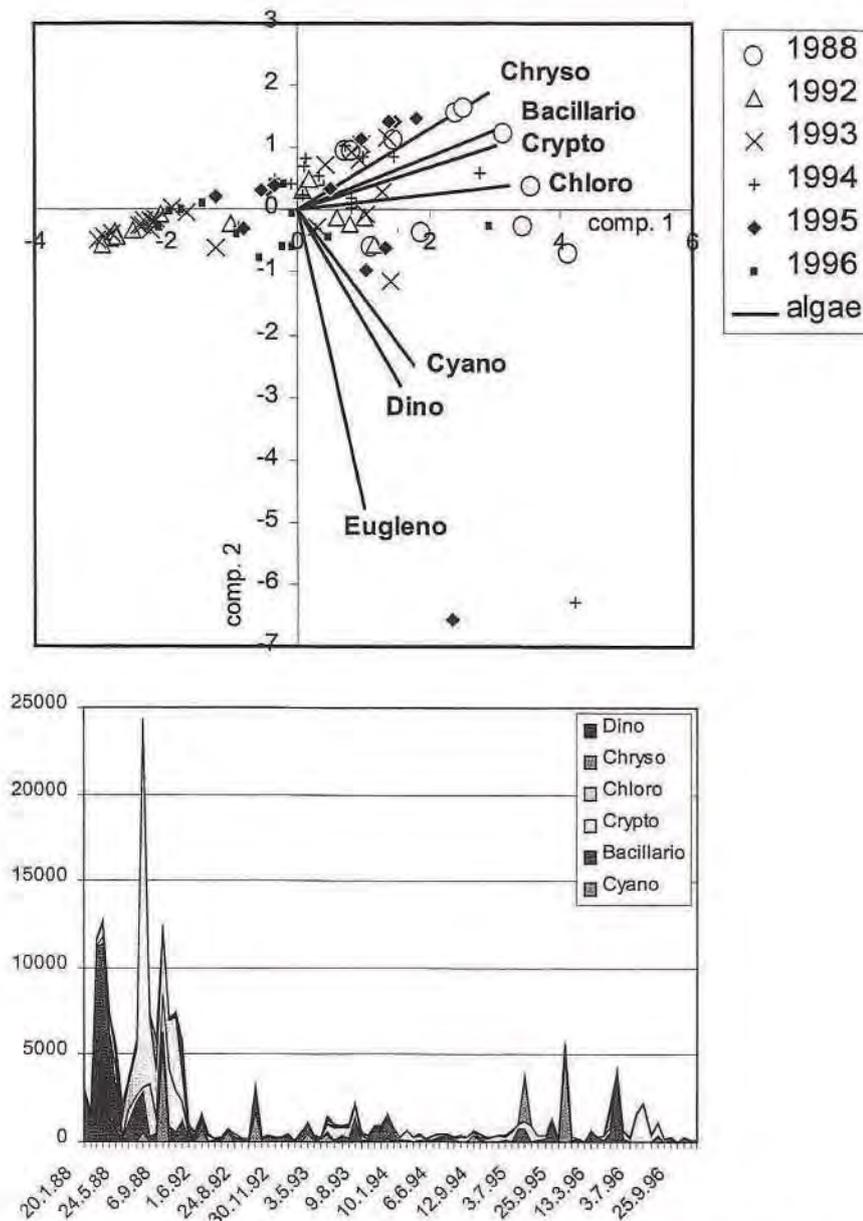


Fig. 10. Top panel: Biplot of the first versus second principal component for phytoplankton composition in 1988 and 1992–1996. The percentage of total variance for the first two components was 46% and 19%. Lower panel: Changes in phytoplankton composition at km 21.1 in 1988 and 1992–1996. Abbreviations: Bacillariophyceae (Bacillario), Chlorophyceae (Chloro), Cryptophyceae (Crypto), Chrysophyceae (Chryso), Cyanobacteria (Cyano), Dinophyceae (Dino), Euglenophyceae (Eugleno).

autumn (e.g. 1992 and 1993). Chrysophyceae and Cryptophyceae have the largest biomasses during the summer season, while Cyanobacteria are characteristic components of the autumn phytoplankton biomass, especially in October 1995 (Fig. 9, top left panel).

PCA-analysis of the biomass data indicates that changes in the plankton are mainly due to quantitative and not to qualitative shifts (Fig. 10, top panel), because the arrangement of data-points along the axis of the first principal component primarily shows differences in size (HENRION et al. 1988). The large reduction of phytoplankton biomass from 1988 to the period 1992–1996 is a result of the proportional decline of all dominant algal classes (see diatoms, chryso-, crypto- and chlorophycean vectors along the first PCA axis) (compare Fig. 10, bottom panel, and Fig. 9). Biomass developments of Cyanobacteria, Euglenophyceae and Dinophyceae are less important, as indicated in Fig. 10 by the number of points scattered around the respective vectors along the axis of the second principal component. The rectangular orientation of these vectors relative to those of the dominant algal classes implies that the three groups mentioned are unrelated to the others.

Discussion

Initial situation

In early 1987 when this investigation began, construction of the flood-relief channel was still unfinished. At that time the average concentrations of most variables, including Chl-a as a measure of algal biomass, indicated that conditions in the New Danube were hypertrophic (FLECKSEDER et al. 1987; DOKULIL 1988), as had already been the case in previous measurements (LÖFFLER 1986). Most of the variables had significant concentration gradients in the upper impoundment, decreasing from high values near the intake weir at km 21.1 to low values further down (DOKULIL 1989; DOKULIL & JANAUER 1989, 1990; DOKULIL et al. 1988). In general, the southern impoundment had lower concentrations, no such gradients, and was covered by dense stands of macrophytes.

The observed nutrient concentrations in the impoundments were caused primarily by high total concentrations of phosphorus and nitrogen ($224 \mu\text{g P l}^{-1}$ and 1.79 mg N l^{-1} , respectively) which were present at that time in the River Danube (WEILGUNI et al. 2000) and were transported into the new channel by groundwater seepage through the artificial Danube Island separating the two watercourses (DOKULIL 1988; HUMPESCH et al. 1994).

A variety of factors and processes influence and alter the dissolved phosphorus components during their passage through the aquifer of Danube Island (see KREUZINGER & MATSCHÉ 2000). The interrelationships between phosphorus concentrations in the river and in the two impoundments are further obscured by rapid turnover of the element. The calculated correlations for total

phosphorus (TP) and total soluble phosphorus (TSP) therefore are not very high but statistically significant (Fig. 2).

Direct input of nutrients from the Danube when the flood-gates are opened are of relatively minor importance for the overall nutrient budgets of the impoundments, because these inputs are only occasional and of short duration (HUMPESCH 1992). However, phytoplankton growth is certainly affected by these short-term pulses (Figs. 5 and 8). Other inputs from precipitation and recreational activities are comparatively unimportant (PICHLER 1994; HUMPESCH 1997).

Oligotrophication

The gradual reduction of nutrient load in the main river (PETTÒ et al. 1991; WEILGUNI et al. 2000) led to diminished transfer in groundwater (KOLROSER 1994), ultimately resulting in reduced nutrient concentrations in the New Danube (DOKULIL & JANAUER 1990; DOKULIL 1993). Differences between fluctuating water levels in the river and relatively static water levels of the impoundments has complicated the input and output of groundwater. As a result of spatially different inputs and processes in the channel, such as the uptake of nutrients, sedimentation and precipitation, north to south gradients of the measured variables developed in the upper impoundment (DOKULIL & FRISK 1993; KREUZINGER & MATSCHÉ 2000). Noticeable gradients were not observed in the southern impoundment because of smaller inputs, shorter distances and massive submerged macrophyte cover. The functional effects of these stands of plants is of decisive importance for the nutrient balance and development of the phytoplankton (DOKULIL & JANAUER 2000; JANAUER & WYCHERA 2000; KREUZINGER & MATSCHÉ 2000).

Assuming that the TN:TP:SRSi ratio of 16:1:17 is a rough estimator for the optimum ratio of these three nutrients in different seasons in the New Danube (Fig. 6), algal growth does not appear to be limited by nitrogen or silica, but apparently is limited by the availability of phosphorus. Throughout the investigation period, phosphorus remained the driving variable.

The quantitative reduction of nutrient concentrations in the impoundments is accompanied by a very marked decrease of chlorophyll-a concentrations and phytoplankton biomass. The ratios of the three measured nutrients, however, remained invariable over time. The TN:TP:SRSi ratios at high biomass in 1988 resemble those of years with low biomass development. Similarly, the large reduction of algal biomass from 1988 to 1992–1996 was not accompanied by major compositional changes of the phytoplankton (Figs. 9 and 10).

Species assemblages are, and have been in the past, mainly a combination of small centric diatoms preferring high SRSi/P ratios, small green algae typical of shallow turbulent situations (C-species, REYNOLDS 1988), and motile fast-grow-

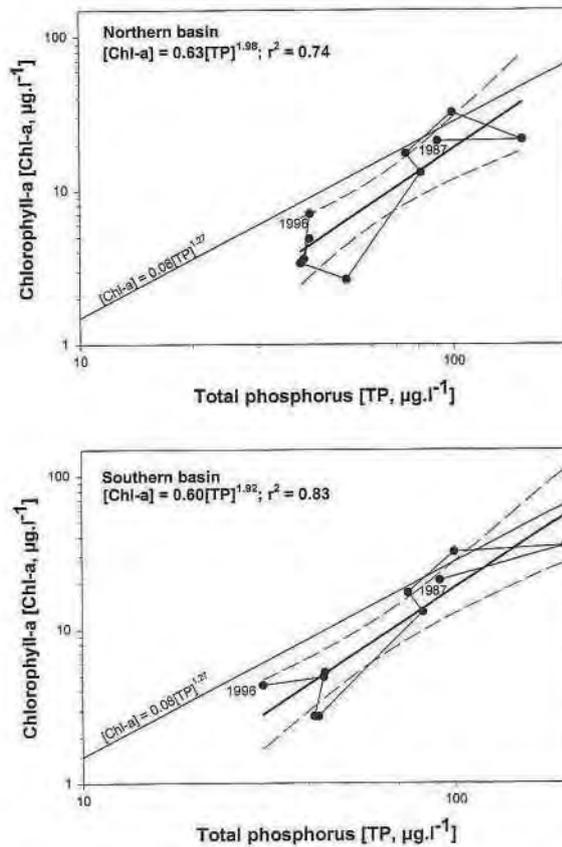


Fig. 11. Mean annual chlorophyll-a versus total phosphorus concentrations for the New Danube in the period 1987–1996. Concentrations of both are in $\mu\text{g l}^{-1}$, plotted on logarithmic scales; lines connect consecutive years. Top panel: upper impoundment (northern basin) at km 21.1. Bottom panel: lower impoundment (southern basin) at km 9.0. The regression equations and r^2 values are given at top left in each panel; regression lines (solid straight lines) and 95% c.l. (dashed curves) are given for the ten yearly data points, and are compared with a VÖLLENWEIDER equation taken from OECD (1982).

ing flagellates (transitional species, OLRİK 1994). Disturbance (R-species) or stress-tolerant species (S-species) have always played a minor role and, in fact, they have become even less important recently (FUX 1991; DOKULIL & TEUBNER 1999).

Long-term changes

Comparison of annual average TP with mean annual Chl-a reveals the noticeable degree of oligotrophication which has taken place in the impoundments over the

10 years of study (Fig. 11). Both variables are highly correlated for both the upper and lower impoundments ($r^2 = 0.74$ and 0.83 , respectively). The equations of both regressions (Fig. 11) are not statistically different from VOLLENWEIDER's equation: $\text{Chl-a} = 0.08 \text{ TP}^{1.27}$ (OECD 1982). Apart from this long-term decrease, short-term effects from nutrient pulses affect the phytoplankton biomass and the Chl-a concentrations. These pulses do not show up in the statistical evaluations, because the peaks are smoothed out by seasonal averaging (Figs. 7 and 10). The reduction of TP over time is not accompanied by a decrease in TN, both in the river and in the New Danube, because phosphorus input is derived primarily from point sources in the catchment whereas nitrogen originates from diffuse runoff (FLECKSEDER 1990). As a result, TN:TP ratios have increased from 1988 to 1996 (Fig. 6; compare also DOKULIL & TEUBNER 1999).

Conclusions

The flood-relief channel New Danube has undergone considerable changes during the 10-year study period from 1987 to 1996, associated with decreasing nutrient inputs from the River Danube, enhancement of water throughput and hence a reduction in retention times (WEILGUNI 2000). Changes in trophic status are substantially manifested by the concurrent decline of phytoplankton biomass. The moderate compositional changes in algae are attributed to nutrient ratios remaining at similar levels, apparent limitation by phosphorus and, in particular, to the shallow, mixed conditions and variable but relatively short retention times of the two impoundments. Pulses of nutrient inputs by floods of short duration lead to peak events in algal growth and biomass.

In general, the trophic status of groundwater seepage systems is entirely dependent on hyporheic inputs. The amount and quality of the inputs, however, is largely dependent on the biogeochemical nature of the subterranean substratum. Any quantitative or qualitative changes in chemical content of the groundwater, resulting from changes in the parent system, are in such cases ultimately reflected in the receiving water.

Acknowledgements

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References

- BARKER, P., FONTES, J.-C., GASSE, F. et al. (1994): Experimental dissolution of diatom silica in concentrated salt solutions and implications for paleoenvironmental reconstruction. – *Limnol. Oceanogr.* **39**: 99–110.
- DOKULIL, M. (1988): Die Nährstoffsituation der Neuen Donau heute und der zu erwartende Zustand nach Errichtung der Donaustaustufe Wien-Freudenau. – *Schriftenr. Cajetan Felder Inst.* **2** (Die ökologische Vernetzung Wiens mit dem Umland): 13–22.
- (1989): Jahresverlauf des Nährstoffeintrages und der Algenentwicklung in der Neuen Donau im Jahre 1988. Zustandsanalyse und Prognose. – Project Report, MA-45, Wien.
- (1993): Long-term nutrient loading and biological response in a flood-water reservoir (Neue Donau) in Vienna, Austria. – *Wat. Sci. Tech.* **28**: 55–63.
- DOKULIL, M. T. & FRISK, T. (1993): Long-term trophic dynamics and predictive model of a flood-water control system of the river Danube in Vienna, Austria. – Internat. Symp. "Transboundary river basin management and sustainable development", RBA Centre Delft Univ. of Technology, 18–22 May 1992. Proceedings **II**: 191–195. UNESCO, Paris.
- DOKULIL, M. T. & JANAUER, G. A. (1989): Die Neue Donau als Badegewässer. Nutzungsprobleme nach Errichtung der Staustufe Wien-Freudenau. – *Der Aufbau, Perspektiven Spezial*, Dezember 1989: 10–14.
- (1990): Nutrient input and trophic status of the "Neue Donau", a high-water control system along the river Danube in Vienna, Austria. – *Wat. Sci. Tech.* **22**: 137–144.
- (2000): Alternative stable states of macrophytes versus phytoplankton in two interconnected impoundments of the New Danube (Vienna, Austria). – *Arch. Hydrobiol., Suppl.* **135** (Large Rivers **12**) (1): 75–83.
- DOKULIL, M., JANAUER, G. A., EISL, L. et al. (1988): Phosphoreintrag und Eutrophierung in der Neuen Donau. – *Der Aufbau, Perspektiven* **9/10**: 73–76.
- DOKULIL, M. T. & TEUBNER, K. (1999): Güteentwicklung der Neuen Donau. 1. Nährstoffe und Phytoplankton. – *Der Aufbau, Perspektiven* **2-3**: 34–36.
- FLECKSEDER, H. (1990): Woher stammen der Phosphor und Stickstoff in der Donau oberhalb und unterhalb von Wien bis zur Machmündung? – In: E. DANECKER & U. H. HUMPECH (Eds.): *ÖN-IAD Symposium: Ein Nationalpark an der Donau*: 19–28. Gessky, Wien.
- FLECKSEDER, H., HUMPECH, U. H., DOKULIL, M. T., HERZIG, A., JANAUER, G. A. & KOHL, W. (1987): Beurteilung der Gewässergüte der Donau und Neuen Donau im Raum Wien. Gegenwärtiger Zustand und Abschätzung der Entwicklung bei Errichtung der Staustufe Wien. – Project Report, MA-45, Wien.
- FUX, S. (1991): Die qualitative und quantitative Phytoplanktonzusammensetzung der Neuen Donau bei Wien (Untersuchungszeitraum 1988). – Master Thesis, Univ. Vienna.
- GILBERT, J. G., DOLE-OLIVIER, M.-J., MARMONIER, P. et al. (1990): Surface water-groundwater ecotones. – In: R. J. NAIMAN & H. DÉCAMPS (Eds.): *The ecology and management of aquatic-terrestrial ecotones. Man and the Biosphere Series* **4**: 199–225. UNESCO, Paris.
- HAMILTON, P. B. (1990): The revised addition of a computerized plankton counter for plankton, periphyton and sediment diatom analyses. – *Hydrobiologia* **194**: 23–30.

- HENRION, G., HENRION, A. & HENRION, R. (1988): Beispiele zur Datenanalyse mit Basic-Programmen. – Deutscher Verlag der Wissenschaften, Berlin.
- HUMPESCH, U. H. (Ed.) (1992): Neue Donau. Badesaison 1991. Veränderungen in der Qualität des Wassers als Folge eines Hochwassers. – Project Report, MA-45, Wien.
- (1997): Neue Donau 1996. Teilstau-Erfahrung. Teil 1: Datenanalyse und Interpretation. – Project Report, MA-45, Wien.
- HUMPESCH, U. H., BERGER, B., ANDERWALD, P. H. et al. (1994): Neue Donau. Badesaison 1993. Badewasserqualität und Nährstoffgehalte unter Einbeziehung des Grundwassereinflusses. Erstellung einer Nährstoffbilanz. – Project Report, MA-45, Wien.
- HUMPESCH, U. H., SCHIEL, W., WEILGUNI, H. & DUJMIC, A. (2000): The New Danube in Vienna (Austria): a flood-relief channel, surrounding wetlands and associated problems for management. – Arch. Hydrobiol., Suppl. **135** (Large Rivers **12**) (1): 3–12.
- JANAUER, G. A. & WYCHERA, U. (2000): Biodiversity, succession and the functional role of macrophytes in the New Danube (Vienna, Austria). – Arch. Hydrobiol., Suppl. **135** (Large Rivers **12**) (1): 61–74.
- KOLROSER, H. (1994): Quantifizierung des Nährstoffeintrags in die Neue Donau in Wien über das Grundwasser: Untersuchung im Rahmen der interdisziplinären Studie „Neue Donau“. – Master Thesis, Univ. Vienna.
- KREUZINGER, N. & MATSCHÉ, N. (2000): Danube Island – an aquifer for nutrient and water quality transfer into the New Danube (Vienna, Austria). – Arch. Hydrobiol., Suppl. **135** (Large Rivers **12**) (1): 23–37.
- LÖFFLER, H. (Ed.) (1986): Limnologische Erhebungen im Bereich der geplanten Staustufe Wien (Neue Donau, Alte Donau, Ölhafen, Donau-Oder-Kanal, Dechant-Lacke und Panozza-Lacke). – Project Report, MA-18, Wien.
- MACKERETH, F. J. H., HERON, J. & TALLING, J. F. (1989): Water Analysis: Some revised methods for limnologists. – Freshwat. Biol. Assoc., Sci. Publ. **36**, 2nd ed.
- NACHTNEBEL, H.-P. (1989): Hydrologische Veränderungen durch das Donaukraftwerk Altenwörth. – In: N. HARY & H. P. NACHTNEBEL (Eds.): Ökosystemstudie Donaustau Altenwörth. Veränderungen durch das Donaukraftwerk Altenwörth. Österr. Akad. Wiss., Univ.-Verlag, Innsbruck.
- NUSCH, E. A. (1980): Comparison of different methods for chlorophyll and phaeopigment determination. – Arch. Hydrobiol., Suppl. Ergebn. Limnol. **14**: 14–36.
- OECD (1982): Eutrophication of waters. Monitoring, assessment and control. – OECD-Publ., Paris.
- OLRIK, K. (1994): Phytoplankton Ecology. Determining factors for the distribution of phytoplankton in freshwater and the Sea. – Miljøprojekt **251**: 1–183, Danish Environ. Protect. Agency, Minist. of Environment, Denmark.
- PETTO, H., FLECKSEDER, H. & HUMPESCH, U. H. (1991): Güte des Wassers der Donau im Bereich der Staustufe Altenwörth (Stromkilometer 1980–2007), 2. Teil: Langzeitentwicklung von 1957–1988. – Österr. Wasserwirtschaft **43**: 71–81.
- PICHLER, B. (1994): Nährstoffeintrag in die Neue Donau über den Niederschlag. – Master Thesis, Univ. Vienna.
- REYNOLDS, C. S. (1988): Functional morphology and the adaptive strategies of freshwater phytoplankton. – In: C. D. SANDGREN (Ed.): Growth and reproductive strategies of freshwater phytoplankton: 388–433. Cambridge Univ. Press.

- ŠMILAUER, P., PRACH, K. & RAUCH, O. (1996): Hydrology and water table dynamics. – In: K. PRACH, J. JENÍK & A. R. G. LARGE (Eds.): Floodplain ecology and management. The Lužnice River in the Třeboň Biosphere Reserve, Central Europe: 37–46. SPB Academic Publ., Amsterdam.
- SOMMER, U. (1988): Growth and survival strategies of planktonic diatoms. – In: C. D. SANDGREN (Ed.): Growth and reproductive strategies of freshwater phytoplankton: 227–260. – Cambridge, Univ. Press, New York.
- TEUBNER, K. (1996): Struktur und Dynamik des Phytoplanktons in Beziehung zur Hydrochemie und Hydrophysik der Gewässer: Eine multivariate statistische Analyse an ausgewählten Gewässern der Region Berlin-Brandenburg. – Ph. D. Thesis. Humboldt-Univ., Berlin.
- TEUBNER, TH., TEUBNER, K. & DOKULIL, M. T. (2000): Use of triangular TN:TP:SRSi-diagrams to evaluate nutrient ratio dynamics structuring phytoplankton assemblages. – Verh. internat. Verein. Limnol. **27** (in press).
- THOMPSON, P.-A. & RHEE, G.-Y. (1994): Phytoplankton responses to eutrophication. – Arch. Hydrobiol., Beih. Ergebn. Limnol. **42**: 126–166.
- UTERMÖHL, H. (1958): Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. – Mitt. Internat. Verein. Limnol. **9**: 1–38.
- VANEK, V. (1987): The interactions between lake and groundwater and their ecological significance. – Stygologia **3**: 1–23.
- (1991): Riparian zone as a source of phosphorus for a groundwater-dominated lake. – Wat. Res. **25**: 409–418.
- WALKER, K. F., THOMAS, M. C. & SHELDON, F. (1992): Effects of weirs on the littoral environment of the River Murray, South Australia. – In: P. J. BOONE, P. CALOW & G. E. PETTS (Eds.): River Conservation and Management: 271–292. John Wiley & Sons, Chichester.
- WEILGUNI, H., HUMPESCH, U. H. & KAVKA, G. G. (2000): Long-term trends of major plant nutrients in the River Danube at Vienna (Austria), the nutrient source for the New Danube. – Arch. Hydrobiol., Suppl. **135** (Large Rivers **12**) (1): 13–21.

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