

Impact of the Formation of Dredged Lakes on the Hydrochemistry and Stable Isotope Content of Porous Shallow Groundwater Fields – A Case Study on Schwarzl Lake in Styria and Weizelsdorfer Lake in Carinthia (Austria)

*Auswirkungen von Baggerseen auf die hydrochemische Beschaffenheit
und isotopische Zusammensetzung seichtliegender Grundwasserfelder –
Fallstudie am Beispiel Schwarzl See (Steiermark) und Weizelsdorfer See (Kärnten),
Österreich*

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1. Introduction

During the past few decades a huge quantity of sand and gravel has been mined from the inter-alpine basins and forelands of the Alps to meet the growing demand for construction material in Austria. On a large number of sites, dredging is continued below the water table of the shallow Quaternary aquifers, ultimately resulting in the formation of artificial groundwater lakes, thereafter called dredged lakes. Many of these lakes have subsequently become recreation centers. Dredging activity caused not only a major change in the landscape of these regions, but also a strong impact, particularly on the quality of the shallow groundwater. Removal of the overburden and, ultimately, exposure of the groundwater and later wider use of the dredged lakes for recreation purposes made the shallow groundwater fields adjacent to the lakes highly vulnerable to pollution.

Previous studies on similar dredged lakes focused on the determination of the hydrologic position of the lakes in shallow groundwater flow systems, and estimation of inflow and outflow rates using hydraulic approaches (J. P. WROBEL, 1980, G. SCHNEIDER, 1983). Stable isotopes (^2H and ^{18}O) were also applied in the last three decades to estimate subsurface inflow and outflow rates (U. ZIMMERMANN, 1978, A. ZUBER, 1983, B. YEHDEGHO et al., 1997) and to determine the flow direction and lake water content in wells situated downstream of dredged lakes (W. STICHLER & P. TRIMBORN, 1980, B. YEHDEGHO et al., 1997). Detailed studies, particularly on the chemical mass budget, the hydrochemical and hydrobiochemical processes involved in dredged lakes, and their impact on the mixing zone, are however rare.

A comprehensive interdisciplinary research program, aimed at working out criteria for the sustainable utilization of dredged lakes for different uses, was initiated in 1990 by the Ministry of Environment, Youth and Family Affairs and by the Ministry of Agriculture and Forestry of the Republic of Austria.

Detailed limnological, hydrochemical and isotopic study was performed in three dredged lake areas with different forms of use and ages, one in northern Austria (the Ornding Lake in Lower Austria) and two in southern Austria (the Schwarzl Lake in Styria and the Weizelsdorfer Lake in Carinthia). This study involves interpretation of the hydrochemical and stable isotope data collected from the later two lake systems. The main aims of the study are

- (1) determining the hydrochemical changes,
- (2) examination of the processes responsible for the changes in concentration of the major chemical species in the dredged lakes and
- (3) assessing the impact of the lakes on the mixing zone.

A steady-state mass balance equation has been employed to calculate the chemical mass budget for the major dissolved species in the lakes. As a result, the processes responsible for the changes in concentration of the chemical components in the lakes could be determined. Furthermore, the influence of the dredged lakes on the adjacent groundwater fields has been studied in some detail, using hydrochemical and stable isotope (deuterium and oxygen-18) data. The variation of the saturation indices of carbonate minerals together with P_{CO_2} have been used as indicators of the extent of interaction between the dredged lakes and the adjacent aquifer. In addition, stable isotope data (deuterium and oxygen-18) has been used to quantify the lake water content in the wells located in the mixing zone of the dredged lakes.

2. Description of embedding aquifers

The Schwarzl and the Weizelsdorfer Lakes (Fig. 1) were created by excavation of predominantly gravelly glacio-fluvial sediments for construction purposes in the past few decades.

In the Schwarzl Lake area dredging commenced in the early 1970s and continued until the late 1980s, exposing approximately 0.45 km² groundwater surface area. Progress reports and technical documents indicate that excavation work started in this area in several pits and, as dredging works gradually expanded, the pits were joined to give two separate open groundwater bodies called Sportler Lake and FKK Lake. Finally, as the present study was underway, the two basins were adjoined in the second week of March 1991 by removing the thin wall of gravelly sediments, becoming one lake called Schwarzl Lake.

Whereas, in the Weizelsdorfer Lake area dredging started in 1980 and ended in 1991, resulting in the formation of approximately 0.11 km² exposed groundwater surface area. Based on echo sounding measurements performed in August 1991, both dredged lakes have comparable average depth of about 6 m and maximum depth of about 10 m. Both lakes are currently used as recreation centers.

The lakes are embedded in shallow phreatic aquifers of fluvio-glacial origin deposited during the Quaternary period. In the Schwarzl Lake area the thickness of the aquifer varies from approximately 10 m at the location of well PB33, close to the western boundary of the small basin known as the "Grazer Feld", to about 15 m in the central part at the location of the BL7 borehole (Fig. 1). Accordingly, based on the groundwater level monitoring data from 1991, the saturated thickness increased from about 5 m to 9 m (B. YEHDEGHO, 1993).

The underlying Neogene argillaceous sediments, of about 250 m in thickness, serve as an aquiclude of the aquifer. The hydraulic conductivity of the aquifer is approximately $(1-3) \times 10^{-3} \text{ m} \cdot \text{sec}^{-1}$. Here, the largest values determined were for the area closest to the dredged lakes (O. OTT & G. SCHICKOR, 1990). According to B. YEHDEGHO et al. (1997), the groundwater flow velocity in the mixing zone of the lake, calculated using hydraulic parameters, deuterium ($\delta^2\text{H}$) and dissolved oxygen data, ranged from 5 to 6 m per day. As it can be deduced from the groundwater contour map shown in fig. 1, the groundwater flow direction in the studied area was from NW to SE.

In the Weizelsdorfer Lake area, the upper part of the glacio-fluvial sediments, consisting of predominantly gravelly sediments (of about 15 m in thickness), forms the main aquifer. The sediments were deposited by fluvial and glacial activities during Pleistocene and Holocene periods. The underlying predominantly silty layer acts as an aquiclude of the shallow aquifer. Based on pumping tests (G. PROBST, 1993), the hydraulic conductivity of the aquifer is approximated at $(1-4) \times 10^{-2} \text{ m} \cdot \text{sec}^{-1}$. In the lake vicinity the groundwater flows from SW to NE.

The studied lakes are typical through-flow systems with no surface inflow or outflow. Hydrologic fluxes involved in the water budget of the lakes are direct precipitation, subsurface inflow, evaporation from the lake surface and subsurface outflow. Climatic water balance, for both above water and land surface, was determined for the investigated areas, using long-term meteorological data.

Table 1 summarizes annual mean values of the long-term meteorological variables and accordingly, calculated evaporation parameters and recharge rates with the standard error of the mean. Lake evaporation was calculated using the PENMAN combined

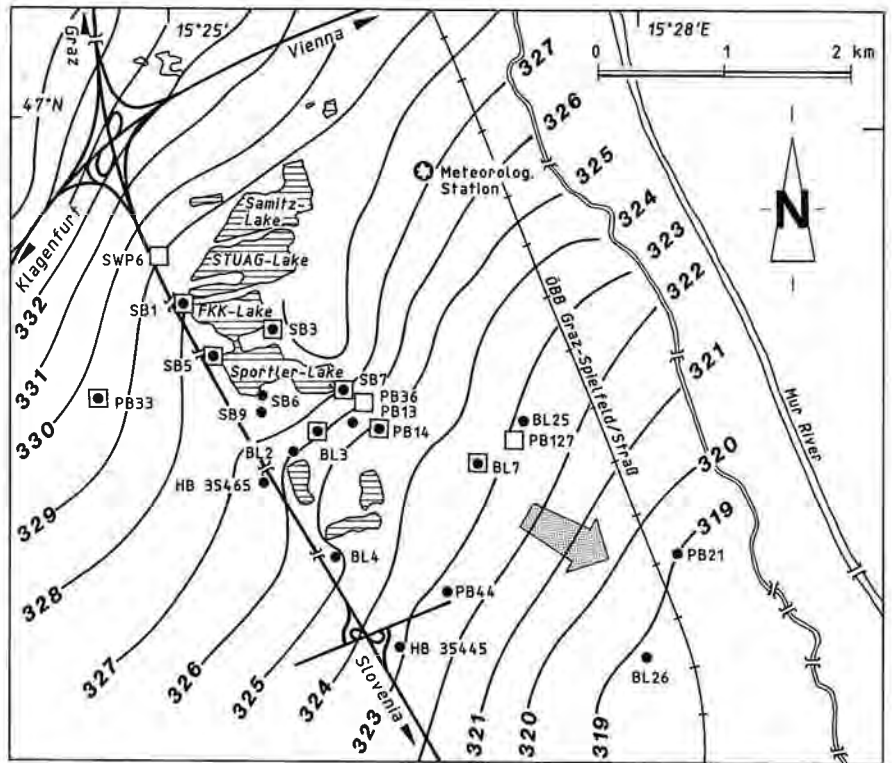


Fig. 1: Location map of the study areas with groundwater table contours and the sampling points. Left side: Schwarzl Lake system. Right side: Weizelsdorfer Lake system. ● denotes stable isotope sampling point and □ hydrochemical sampling point. (Continuation p. 61.)
 Lage der Untersuchungsgebiete mit Grundwasserisolinien und Probenahmestellen. Links: Schwarzl Baggersee. Rechts: Weizelsdorfer Baggersee. Symbole: ● Probenahmestelle für Isotope und □ für Chemie. (Fortsetzung S. 61.)

3. Hydrochemical and isotopic monitoring

Detailed hydrochemical and isotopic monitoring was performed from November 1990 to March 1993 in the Schwarzl Lake and the Weizelsdorfer Lake areas. Water samples for laboratory hydrochemical analysis and stable isotope (^2H and ^{18}O) determination were collected and in situ measurements performed monthly in the studied lakes and observation wells in the adjacent groundwater fields (Fig. 1). Lake water samples were collected at different depths (0.5, 1 and thereafter at 2 m intervals) for hydrochemical analysis from the two basins of the Schwarzl Lake ("FKK" Lake and "Sportler" Lake) and from one profile in the Weizelsdorfer Lake. At the same stations, field parameters including specific electrical conductivity, water temperature and dissolved oxygen content, were measured monthly at every one meter intervals. Water samples for stable isotope determination were collected at approximately 0.5 m below the surface. Depth sampling (at one meter intervals) was performed for isotope determination at the two basins of the Schwarzl Lake in November 1990 and August 1991, and at the Weizelsdorfer Lake in December 1990, April, July and November 1991.

A total of 19 observation wells in the Schwarzl Lake system and 14 in the Weizelsdorfer Lake system were monitored. As shown in fig. 1, the observation wells PB33, SWP6, SB1 and SB5 in the Schwarzl Lake area, and S1, S2, S9 and H030 in the Weizelsdorfer Lake area are located upstream of the studied lakes. The remaining wells are situated downstream of the dredged lakes. To collect representative water samples, the wells were pumped for at least 20 minutes prior to in situ measurement and collection of water samples.

Water temperature, pH, specific electrical conductivity and dissolved oxygen content were measured in situ by lowering the respective probes. HCO_3^- concentration was also determined in situ by titration immediately after obtaining the samples. The major cations, Ca^{2+} , Mg^{2+} , Na^+ and K^+ , were analyzed by Standard Atomic Emission Spectrometry with Inductively Coupled Plasma Excitation (ICP-AES); the anions, Cl^- , NO_3^- and SO_4^{2-} were measured by a High Performance Liquid Chromatography (HPLC), and SiO_2 was determined spectrophotometrically with an ammonium molybdate reagent.

Deuterium and oxygen-18 (^2H and ^{18}O) contents were determined mass spectrometrically with an overall precision of 1 ‰ and 0.1 ‰, respectively. The values are expressed conventionally in delta notation as per mil deviation from the V-SMOW (Vienna Standard Mean Ocean Water).

4. Interpretation of hydrochemical data

4.1. Distribution of chemical parameters

Inspection of the hydrochemical analysis data from the lakes and adjacent groundwater fields revealed that the ions Ca^{2+} , Mg^{2+} and HCO_3^- dominate the chemical character of the studied systems. Exposure of the shallow aquifers provoked a substantial change in the hydrochemical composition of lake water and the shallow groundwater in the mixing zone. The specific electrical conductivity sank on average from approximately 850 in the groundwater inflow to $580 \mu\text{S} \cdot \text{cm}^{-1}$ (25°C) in the Schwarzl Lake, and from 565 to $475 \mu\text{S} \cdot \text{cm}^{-1}$ in the Weizelsdorfer Lake. Groundwater inflow to the Schwarzl Lake and the Weizelsdorfer Lake has a pH of approximately 7.3 and 7.5, respectively,

and changed to more basic (pH of about 8.0) in both lakes. With an average oxygen content of about 11 mg/l in the lakes and about 9 mg/l in the upstream groundwater, the studied systems depicted oxidizing character.

Changes in concentration of the major dissolved solutes in the lakes and the processes involved are discussed later in detail. Here, based on the regularities in the abundance of the cations and anions, it is attempted to characterize briefly the spatial variation of the hydrochemical composition of the shallow groundwater in the influence area of the lakes. In the groundwater upstream of the lakes the distribution order of the major cations reads: $r\text{Ca}^{2+} > r\text{Mg}^{2+} > r\text{Na}^+ > r\text{K}^+$, where r is a reaction value in meq/l. While bicarbonate made up the dominant anion in both studied systems, the abundance sequence of Cl^- , NO_3^- and SO_4^{2-} ions was variable. In the Schwarzl Lake area the distribution of the anions has the order $r\text{HCO}_3^- > r\text{Cl}^- > r\text{NO}_3^- > r\text{SO}_4^{2-}$ and in the Weizelsdorfer Lake area $r\text{HCO}_3^- > r\text{SO}_4^{2-} > r\text{Cl}^- \cong r\text{NO}_3^-$. This is due to different amounts of artificial Cl^- and NO_3^- ion inputs to the groundwater. Salt spray used during winter for de-icing roads and highways and intensive fertilization practices, particularly in the Schwarzl Lake area caused a substantial increase in Cl^- and NO_3^- concentration in groundwater. In the lake water and the groundwater in the mixing zone the order of mobility of the cations was the same for the upstream groundwater. On the other hand, the distribution of the major anions in the dredged lakes as well as in the downgradient groundwater field differed from that of the groundwater inflow; in both lake systems the distribution order was: $r\text{HCO}_3^- > r\text{SO}_4^{2-} > r\text{Cl}^- > r\text{NO}_3^-$.

4.2. Temporal variation

Peaks attributable to fertilization activities and road-salting during winter were noticeable in the time series of the ions NO_3^- , Na^+ and Cl^- in the upstream wells of the Schwarzl Lake, whereas the remaining chemical components did not show significant temporal change. On the other hand, water temperature and dissolved oxygen content of the lakes exhibited distinct seasonality in their temporal distribution (Fig. 2). High water temperature was measured during the summer months and low during winter. The temporal variation of dissolved oxygen content was converse due to the inverse relationship between temperature and solubility of oxygen gas. Concentration of NO_3^- , Ca^{2+} and HCO_3^- ions also varied seasonally in the lakes.

In the Weizelsdorfer Lake high NO_3^- concentration was measured for the winter months, decreasing continuously throughout spring, summer and early autumn until reaching a minimum in October (Fig. 3). This reflects the seasonal cycle of biological activity in the lake (photosynthesizing plants assimilate nitrogen from NO_3^- available in the lake water). On the other hand, the seasonal change of NO_3^- concentration in the Schwarzl Lake was rather not distinct; higher NO_3^- concentrations were measured from late spring to summer and lower in winter which is in anti-phase to the seasonal biological cycle. This could be due to the masking effect of the delayed NO_3^- concentration changes in the upstream lakes (STUAG Lake and Samitz Lake). Also, the distribution of HCO_3^- and Ca^{2+} ions in the lakes followed the seasonal climatic changes for the study areas. In both lakes broad maximum in winter and minimum in summer have been observed (Fig. 4).

The seasonality signature of water temperature and dissolved oxygen content observed in the lakes is also propagated into the downgradient groundwater fields. This could be demonstrated using the time variation of water temperature and dissolved oxygen of the Schwarzl Lake and the observation wells SB7, PB36, PB14 and BL7, situated

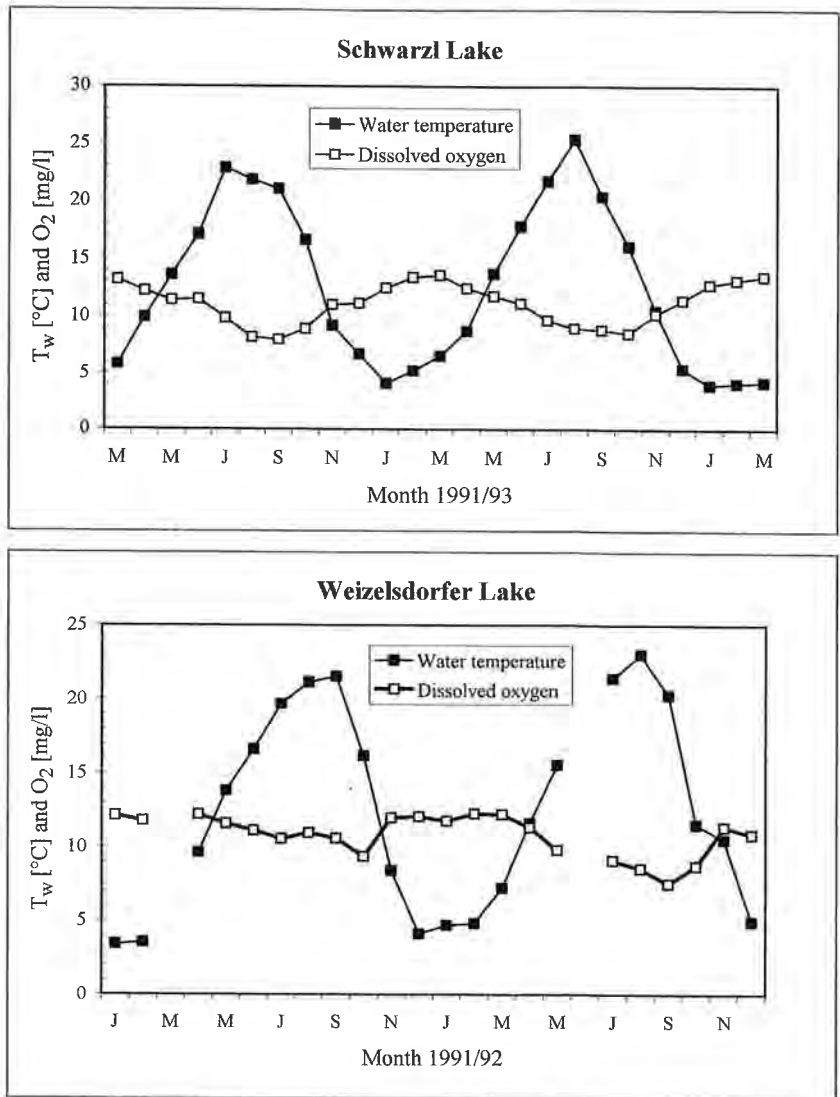


Fig. 2. Temporal variation of water temperature and dissolved oxygen content in the studied lakes. Jahreszeitliche Schwankungen der Wassertemperatur und des gelösten Sauerstoffgehaltes in den Baggerseen.

in the main axis of the mixing zone (Fig. 5). Apparently, the peaks and troughs are temporally shifted (delayed) and the amplitudes dampened with increased distance from the downstream shore of the lake. Seasonal variation of water temperature could clearly be recognized only in the wells that lie very close to the lake (SB7 and PB36). The seasonal change of water temperature in SB7 was almost identical with that in the lake (FKK symbolizes FKK Lake). On the other hand, the seasonality of dissolved oxygen could evidently be traced as far as PB14 (about 475 m from the southeastern end of the lake).

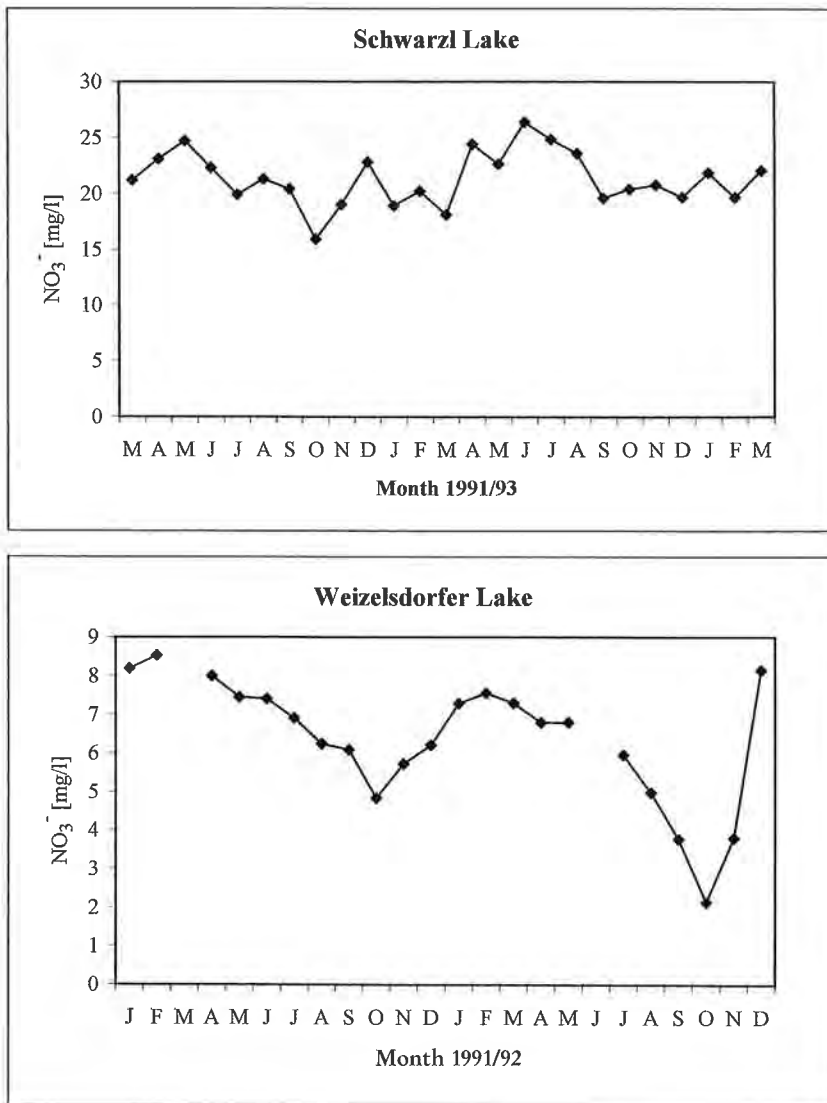


Fig. 3: Temporal variation of NO₃⁻ concentration in the dredged lakes.
Jahreszeitliche Schwankungen des NO₃⁻-Gehaltes in den Baggerseen.

4.3. Saturation indices of carbonate minerals and P_{CO2}

Availability of a significant amount of carbonate sediments in the Quaternary glacio-fluvial deposits combined with higher reactivity of carbonate minerals resulted in the domination of Ca²⁺, Mg²⁺ and HCO₃⁻ ions in the shallow groundwater systems under investigation (Tab. 4). Furthermore, a major change in the chemical composition of lake water was induced by the exposure of the shallow groundwaters by the formation of dredged lakes. In particular, the concentration of Ca²⁺, Mg²⁺ and HCO₃⁻ was modified considerably, leading ultimately to the alteration of the saturation state with respect

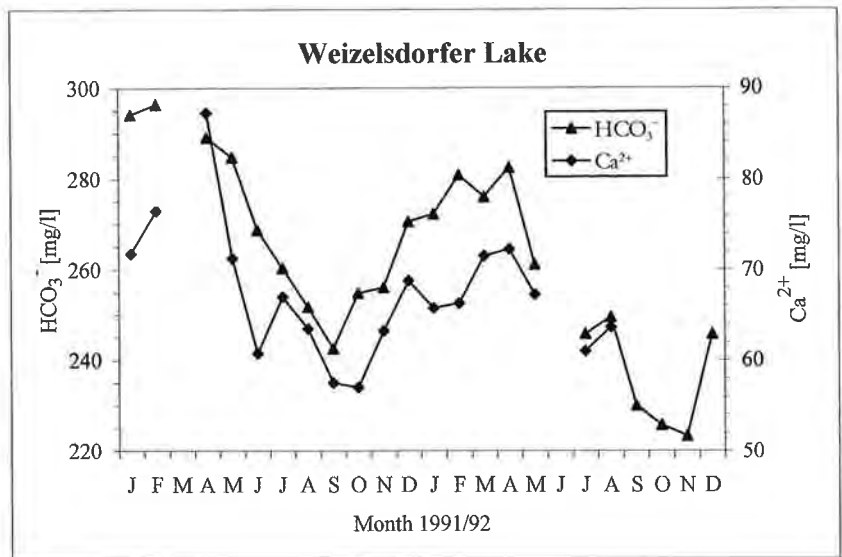
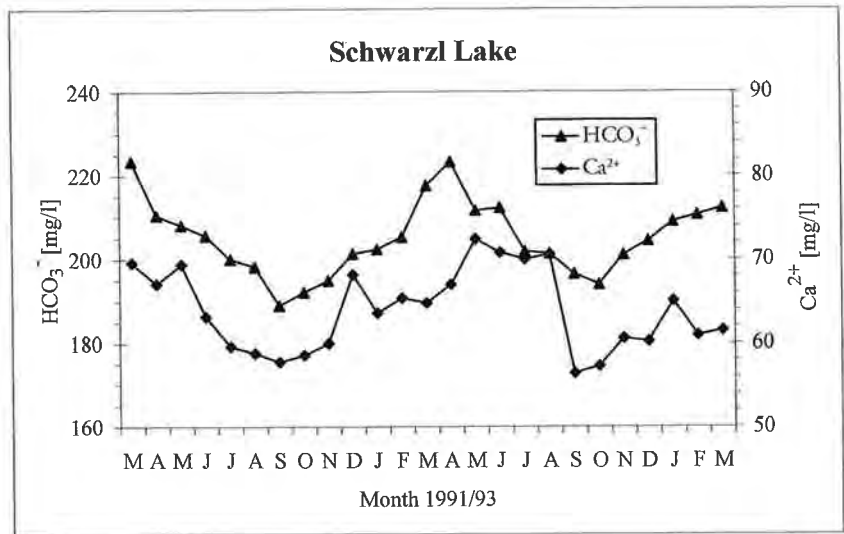


Fig. 4: Seasonality of Ca²⁺ and HCO₃⁻ in the dredged lakes.
Jahreszeitliche Schwankungen des Ca²⁺- and HCO₃⁻-Gehaltes in den Baggerseen.

to calcite and dolomite minerals in lake water and the groundwater in the mixing zones of the studied lakes.

Saturation indices of the carbonate minerals and the corresponding equilibrium concentration of dissolved CO₂ were calculated based on the monthly chemical concentrations of the major ions, field pH and water temperature using the hydrogeochemical speciation program, WATEQF (L. N. PLUMMER et al., 1976). Saturation index (SI) of carbonate minerals was calculated from the equation:

$$SI = \log (IAP/K), \quad (\text{Eq. 1})$$

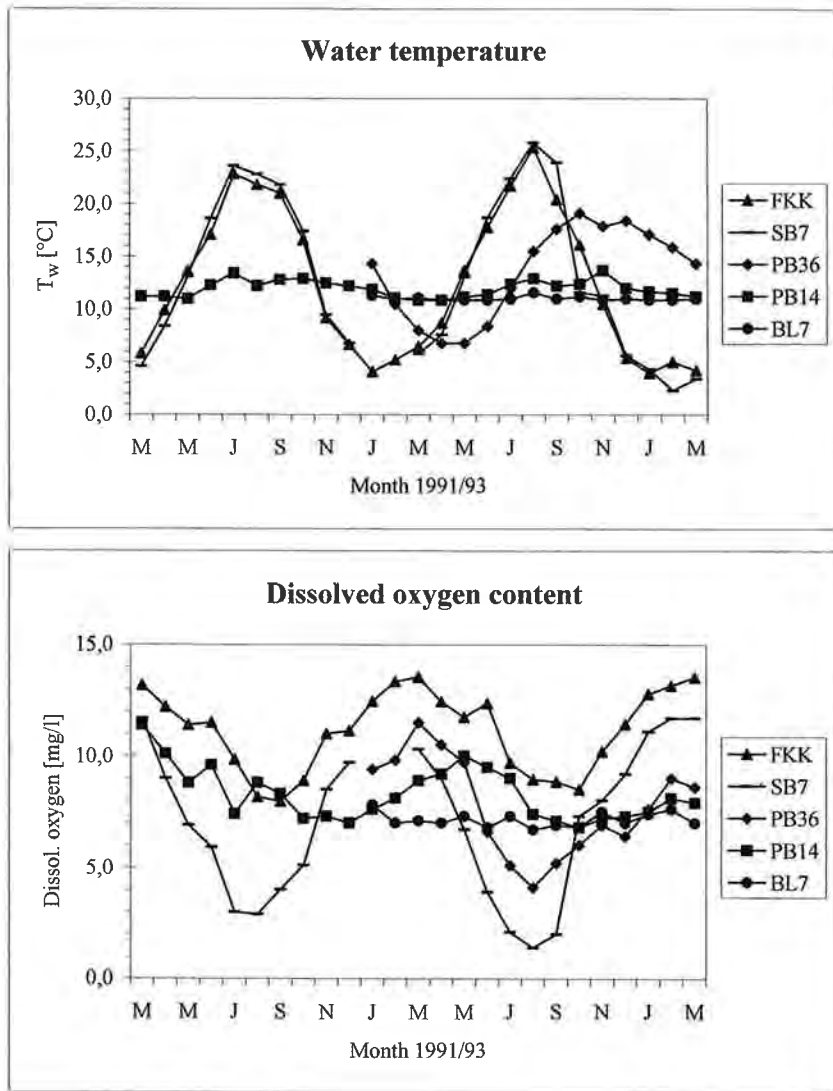


Fig. 5: Propagation of the seasonality signature of water temperature and dissolved oxygen into the groundwater sampling points in the mixing zone of the Schwarzl Lake.
 Fortpflanzung der jahreszeitlichen Schwankungen der Wassertemperatur und des gelösten Sauerstoffes in die Grundwassermeßstellen in der Mischungszone der Schwarzl Baggerseen.

where IAP is the activity product of the ions and K is the equilibrium solubility product for the mineral involved at sample temperature and standard pressure. SI value 0 indicates equilibrium, > 1 supersaturation and < 1 undersaturation of the solution with respect to the mineral considered.

The equilibrium CO_2 partial pressure (P_{CO_2}) in the sampled carbonate system was derived from the equation:

$$P_{\text{CO}_2} = (\alpha_{\text{HCO}_3^-} \cdot \alpha_{\text{H}^+}) / (K_1 \cdot K_{\text{H}}), \quad (\text{Eq. 2})$$

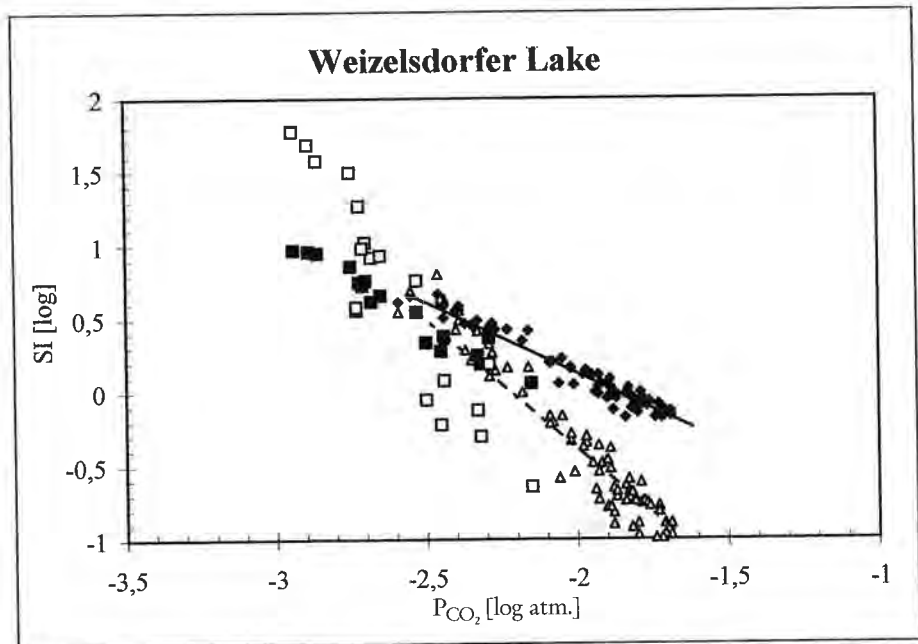
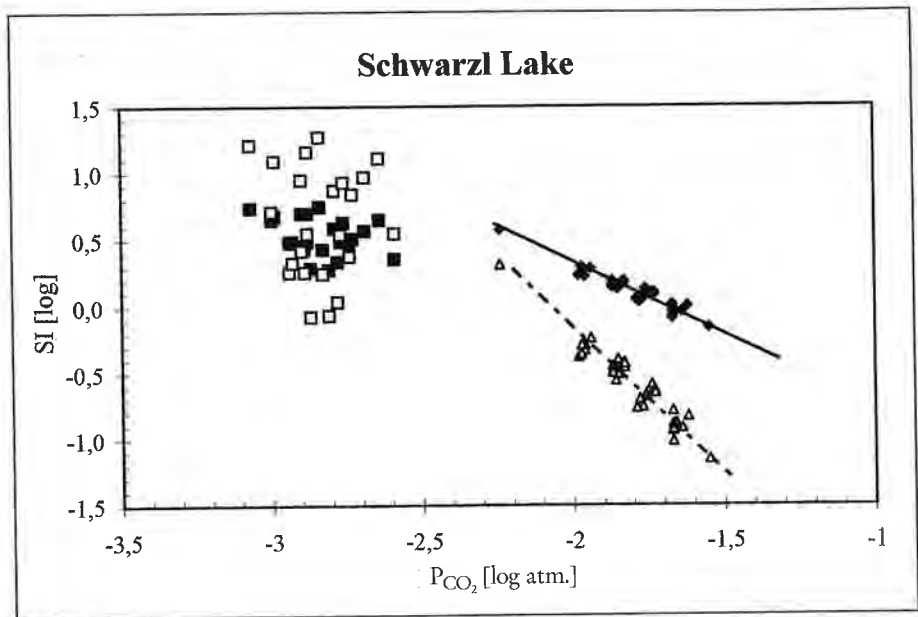


Fig. 6: Plot of the monthly saturation index values vs. equilibrium P_{CO_2} in atm. (in log units).
 ■ denotes $SI_{calcite}$ vs. P_{CO_2} data points and □ $SI_{dolomite}$ vs. P_{CO_2} data points of lake water samples;
 ◆ denotes $SI_{calcite}$ vs. P_{CO_2} data points and △ $SI_{dolomite}$ vs. P_{CO_2} data points of groundwater
 inflow samples.
 Darstellung des Karbonatsättigungsindizes gegen P_{CO_2} (log). Symbole: ■ $SI_{calcite}$ vs. P_{CO_2} und
 □ $SI_{dolomite}$ vs. P_{CO_2} in den Baggerseen; ◆ $SI_{calcite}$ vs. P_{CO_2} und △ $SI_{dolomite}$ vs. P_{CO_2} in den Grund-
 wassermeßstellen im Zustrombereich der Baggerseen.

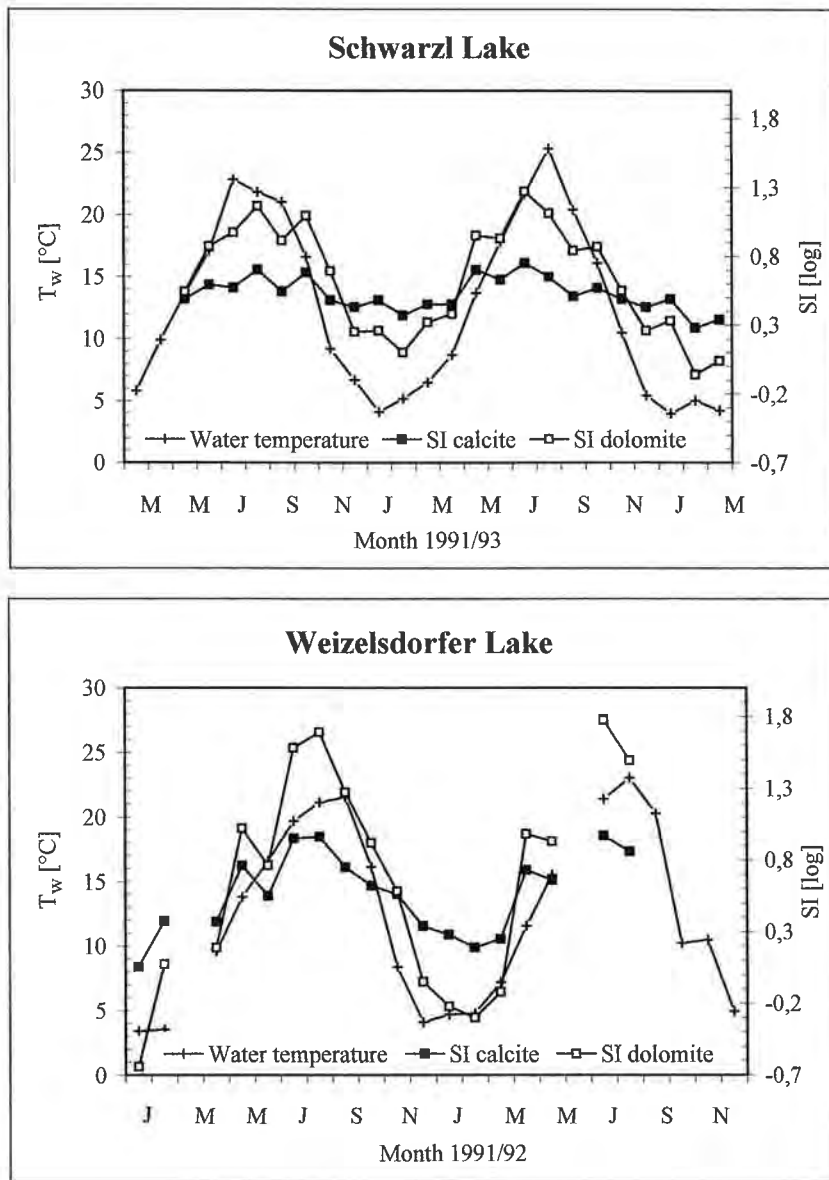


Fig. 7: Seasonal variability of $SI_{calcite}$ and $SI_{dolomite}$ in the studied lakes.
Jahreszeitliche Variabilität des $SI_{calcite}$ und $SI_{dolomite}$ in den untersuchten Baggerseen.

where $\alpha_{HCO_3^-}$ and α_{H^+} are HCO_3^- and H^+ activities, respectively; K_1 and K_H are accordingly the first dissociation constants of $H_2CO_3^*$ and the HENRY's law constant for CO_2 gas dissolution in water.

The results of the SI calculation revealed that the inflowing groundwater to both lakes was weakly supersaturated with respect to calcite but undersaturated with respect to dolomite. The average P_{CO_2} values were typical for normal soils, approximately

$10^{-1.8}$ atm. (about 1.60 vol.%) in the Schwarzl Lake area and $10^{-2.0}$ atm. (1.00 vol.%) in the Weizelsdorfer Lake area. Monthly SI_{calcite} and SI_{dolomite} from the upstream observation wells and lakes were plotted against the corresponding calculated P_{CO_2} (Fig. 6). The data points formed an inverse linear relationship that characterizes the carbonate equilibrium state in the groundwater inflow to the lakes. On the other hand, the data points of the monthly lake water samples were irregularly scattered. This is mainly attributed to the seasonal variation of lake temperature. As shown in Fig. 7, the temporal change of SI_{calcite} and SI_{dolomite} strongly adhered to the seasonal change in water temperature, i.e. higher saturation indices were obtained for summer and lower for winter months. It should also be noted that the seasonality of the saturation indices of dolomite was much stronger than the one of calcite. From spring to autumn SI_{dolomite} surpassed SI_{calcite} and vice versa for winter. This can be explained by the variable effect of temperature on the solubility of the calcite and dolomite. According to R. A. FREEZE & J. A. CHERRY (1979), the solubility of dolomite is enhanced at lower temperatures compared to that of calcite. On average, the lake water samples are supersaturated with respect to both carbonate minerals, with dolomite supersaturation exceeding that of calcite. Equilibrium partial pressures of CO_2 calculated for the samples are about $10^{-2.9}$ atm. for the Schwarzl Lake and $10^{-2.6}$ atm. for the Weizelsdorfer Lake. These values are significantly lower than that of the groundwater inflow, but larger than the P_{CO_2} in the atmosphere ($10^{-3.5}$ atm.).

5. Estimate of the chemical changes in dredged lakes

Quantification of the resulting chemical changes on the major dissolved chemical components is of major importance in evaluating the hydrogeochemical and biochemical alteration due to the formation of dredged lakes. It also provides a basis for decisions regarding the location of future projects for sand and gravel mining in shallow groundwater fields, especially when the porous aquifers are exploited for water supply. The chemical mass budget of the investigated through-flow dredged lakes was calculated by employing the steady-state mass balance equation based on conservation of mass (R. E. STAUFER & B. D. WITTCHEN, 1992):

$$Q_I C_I + P C_P - Q_O C_O - E C_E = \nabla F, \quad (\text{Eq. 3})$$

where Q_I and Q_O are groundwater inflow and outflow rates, respectively; P and E are direct precipitation and lake evaporation rates, respectively. C_I , C_P , C_O and C_E are solute concentrations in the various fluxes denoted by the subscripts and ∇F is an in-lake source/sink function.

5.1. Hydrologic fluxes

Inflow and outflow rates as well as the chemical composition of the different fluxes must be determined first to calculate the chemical budget of a lake. For this purpose, precipitation was obtained from nearby weather stations and evaporation was calculated from the PENMAN combined equation using meteorological data. The subsurface inflow and outflow rates to/from the dredged lakes were determined employing stable isotope mass balance equation using the stable isotopes of water, deuterium and oxygen-18. The theoretical background for the application of stable isotopes for this purpose is well

documented in U. ZIMMERMANN (1978), A. ZUBER (1983), R. GONFIANTINI (1986), D. P. KRABENHOFT et al. (1990), and B. YEHDEGHO et al. (1997).

For a well mixed lake in a hydrologic and an isotopic steady state, the subsurface components are determined by solving the hydrologic and isotope mass balance equations (Eq. 4 and 5):

$$dV_L/dt = I_S + I_G + P - O_G - E, \quad (\text{Eq. 4})$$

$$d(\delta_L V_L)/dt = I_S \delta_S + I_G \delta_G + P \delta_P - O_G \delta_L - E \delta_E, \quad (\text{Eq. 5})$$

where V_L is lake volume; I_G and O_G are groundwater inflow and outflow rates, respectively; I_S is the seepage component from the upstream lake (valid only for the Schwarzl Lake; in the case of the Weizelsdorfer Lake, I_S has to be adjusted to zero). δ_L , δ_S , δ_G , δ_P and δ_E are the isotopic contents of the lake water and the various hydrologic fluxes denoted by the subscripts. Except for evaporation, all isotopic contents were determined from samples of the different hydrologic fluxes. Isotopic content of evaporation flux (δ_E) was determined from the equation proposed by H. CRAIG & L. I. GORDON (1965) employing isotopic contents of lake water and atmospheric vapor above the evaporating surface, as well as water-based meteorological data (temperature at the evaporating lake surface and relative humidity normalized to the temperature of the lake surface).

Lake water balance calculation was performed assuming that the dredged lakes under consideration are in a hydrologic and an isotopic steady state. This assumption is plausible for dredged lakes that were exposed more than 10 years ago before the beginning of present study and further whose evaporation rate is very small compared to the through-flow rate. Vertical profiles of relevant physico-chemical parameters (water temperature and dissolved oxygen content) and stable isotope data revealed that the dredged lakes under study were well mixed. Table 2 contains the average isotopic contents of oxygen-18 and deuterium and relevant meteorological data for 1991 used for the calculation. The meteorological variables were obtained for the Schwarzl Lake from the weather station at Thalerhof Airport, Graz, located about 1.5 km in the NE of the lake and for the Weizelsdorfer Lake from Klagenfurt Airport, about 10 km in the SW of the study area. The stable isotopic content of precipitation was obtained from the meteorological station on the campus of the University of Graz, 13 km in the NE of the Schwarzl Lake

Tab. 2: Meteorological values and stable isotopic contents for 1991 used to determine the lake water balance of the Schwarzl Lake and the Weizelsdorfer Lake.

Meteorologische und isopenhydrologische Daten für 1991, die für die Erstellung der Wasserbilanz des Schwarzl Baggersees und Weizelsdorfer See herangezogen wurden.

	Meteorological values			
	Lake water temperature [°C]	Relative humidity [%]	Precipitation [mm]	Evaporation [mm]
Schwarzl Lake	12.9	62	1107	847
Weizelsdorfer Lake	12.5	64	1210	725
Stable isotopic content $\delta^{18}\text{O}$, $\delta^2\text{H}$ (‰)				
	Precipitation	Groundwater inflow	Upstream lake	Lake water
Schwarzl Lake	- 8.7, -58.9	- 8.2, -56.6	-7.0, -53.2	-6.5, -50.3
Weizelsdorfer Lake	-10.1, -71.0	-10.3, -71.9	-	-9.6, -67.8

Tab. 3: Inflow/outflow rates (l/sec) to/from the studied lakes for 1991. *Subsurface inflow to the Schwarzl Lake comprises the seepage from the upstream STUAG Lake (approximately 70 l/sec) and the groundwater inflow (approximately 118 l/sec).

Zu- und Abflußrate (in l/s) der untersuchten Baggerseen für 1991. * Unterirdischer Zustrom des Schwarzl Baggersees, beinhaltet Infiltration aus dem obstrom liegenden STUAG Baggersee (ca. 70 l/s) und Grundwasserzustrom (ca. 118 l/s).

	Parameter	Schwarzl Lake	Weizelsdorfer Lake
Inflow	Precipitation	16	4
	Groundwater inflow	188*	72
Outflow	Evaporation	12	3
	Groundwater outflow	192	73

and from the meteorological station at Kirschentheur, about 5 km in the E of the Weizelsdorfer Lake.

Volumetric fluxes (l/sec) of the hydrologic components of the studied lakes are summarized in tab. 3. The subsurface inflow and outflow rates to/from the lakes represent the average values obtained from the deuterium and oxygen-18 data. The through-flow rates of the Schwarzl Lake and the Weizelsdorfer Lake were approximately 190 l/sec and 70 l/sec, respectively. Subsurface inflow and outflow are the principal hydrologic components of the lakes; precipitation accounted for only about 8 % and 6 % of the total flux to the Schwarzl Lake and the Weizelsdorfer Lake, accordingly. The mean residence time of water in the lakes (lake volume/volumetric flux) was accordingly about five and four months.

5.2. Chemical fluxes of major dissolved solutes

Concentrations of the major chemical components for which the chemical mass balance was performed are summarized in tab. 4. Average concentration of the chemical species from the piezometers SB1 and SB5, and from S1 and S2 represented the composition of the groundwater inflow to the Schwarzl Lake and the Weizelsdorfer Lake, respec-

Tab. 4: Average concentration (mg/l) of the chemical components for 1991 (P – precipitation, I_G – groundwater inflow and O_G – the lake water) used for determining the chemical mass balance of the lakes. HCO_3^- and SiO_2 content of precipitation was not determined (n.d.).

Konzentration der chemischen Inhaltstoffe (mg/l) für 1991 (im P – Niederschlag, I_G – Grundwasserzufluß und O_G – Seewasser), die für die Erstellung der Seestoffbilanz angewandt wurden. HCO_3^- und SiO_2 -Konzentration in Niederschlagsproben wurden nicht gemessen (n.d.).

Chemical components	Schwarzl Lake			Weizelsdorfer Lake		
	P	I_G	O_G	P	I_G	O_G
Ca^{2+}	0.34	111.45	62.70	0.10	81.07	67.30
Mg^{2+}	0.03	16.38	21.32	0.01	19.59	20.50
Na^+	0.12	26.06	17.85	0.60	4.20	3.30
K^+	0.08	2.57	3.43	0.01	1.45	1.80
HCO_3^-	n.d.	333.94	198.81	n.d.	318.6	261.90
Cl^-	0.18	50.40	37.09	0.12	5.44	4.70
NO_3^-	4.43	56.21	22.14	5.77	8.10	6.60
SO_4^{2-}	2.31	36.72	55.19	3.23	24.64	27.70
SiO_2	n.d.	12.67	3.35	n.d.	4.48	2.20

tively. Solute influx to the lakes via precipitation was obtained from M. F. KALINA & H. PUXBAUM (1995). Chemical data on dryfall was unfortunately not available for the study areas. Therefore, its contribution could not be taken into account in the chemical balance calculation. Concentrations of the chemical components of the lake water were determined by averaging the monthly values at different lake depths. In eq. 3, chemical composition of the subsurface outflow was considered to be identical with that of the lake water. Furthermore, chemical loss from the lakes by evaporation was also assumed to be negligible, implying that the resulting mass flux was nil.

The result of the chemical mass budget of the lakes is summarized in tab. 5. According to B. YEHDEGHO et al. (1997), the uncertainty of lake water balance obtained using stable isotope mass balance method is approximated at 10–20 %. The standard error of the mean values of the chemical components in groundwater inflow and lake water samples given in tab. 4 was under 10 %. So, the calculated chemical mass fluxes are probably within 20–30 % of uncertainty.

The concentration of the dissolved solutes was modified considerably in the lakes

Tab. 5: Flux of major chemical components (in mol/year) for the studied dredged lakes, based on lake water balance and chemical data for 1991. * Average concentration of the samples collected from the FKK Lake and the Sportler Lake is used for computing the chemical balance of the Schwarzl Lake.

Eintrag und Austrag der gelösten Inhaltsstoffe (in mol/Jahr) für die untersuchten Baggerseen, basierend auf die Seewasserbilanz- und hydrochemischen Daten von 1991. * Zur Erstellung der Stoffbilanz des Schwarzl Sees wurde die mittlere Konzentration der aus FKK See und Sportler See gezogenen Wasserproben zugrunde gelegt.

Schwarzl Lake						
Chemical species	Inflow		Outflow* O _G (×10 ⁶)	Net balance (×10 ⁶)	Dilution (×10 ⁶)	Source/sink function (×10 ⁶)
	I _G (×10 ⁶)	P (×10 ³)				
Ca ²⁺	16.52	4.29	9.49	-7.03	-4.10	-2.93
Mg ²⁺	4.05	0.63	5.38	1.33	-1.01	2.34
Na ⁺	6.72	2.63	4.70	-2.02	-1.67	-0.35
K ⁺	0.39	1.04	0.53	0.14	-0.10	0.24
HCO ₃ ⁻	32.46	—	19.73	-12.73	-8.06	-4.67
Cl ⁻	8.42	2.56	6.33	-2.09	-2.09	0.00
NO ₃ ⁻	5.38	36.05	2.16	-3.26	-1.34	-1.92
SO ₄ ²⁻	2.27	12.14	3.48	1.21	-0.56	1.77
SiO ₂	1.25	—	0.34	-0.91	-0.31	-0.60
Weizelsdorfer Lake						
Chemical species	Inflow		Outflow O _G (×10 ⁶)	Net balance (×10 ⁶)	Dilution (×10 ⁶)	Source/sink function (×10 ⁶)
	I _G (×10 ⁶)	P (×10 ³)				
Ca ²⁺	4.60	0.32	3.87	-0.73	-0.53	-0.20
Mg ²⁺	1.85	0.05	1.97	0.12	-0.21	0.33
Na ⁺	0.41	3.29	0.33	-0.08	-0.05	-0.03
K ⁺	0.08	0.03	0.11	0.03	-0.01	0.04
HCO ₃ ⁻	11.86	—	9.88	-1.98	-1.36	-0.62
Cl ⁻	0.35	0.43	0.31	-0.04	-0.04	0.00
NO ₃ ⁻	0.30	11.74	0.25	-0.06	-0.03	-0.03
SO ₄ ²⁻	0.58	4.24	0.66	0.08	-0.07	0.15
SiO ₂	0.17	—	0.08	-0.09	-0.02	-0.07

by dilution and in-lake source/sink function. The first was estimated using the change in chloride concentration as a measure for the dilution from direct precipitation. Chloride has a conservative chemical behavior in natural waters compared to other major ions (J. D. HEM, 1985). Therefore, the decrease in chloride concentration in the investigated lakes was considered to be entirely due to the dilution effect. Based on concentration data from 1991, a dilution effect of about 25 % has been revealed for the Schwarzl Lake and about 11 % for the Weizelsdorfer Lake. The in-lake source/sink function pertinent to hydrogeochemical and biochemical reactions in the lakes was thus estimated by subtracting the dilution effect from the net annual chemical budget. As shown in tab. 5 (last column), in both lakes negative balance was obtained for Na^+ , Ca^{2+} , HCO_3^- , NO_3^- and SiO_2 , and positive for Mg^{2+} , SO_4^{2-} and K^+ .

It must be noted that the dilution value obtained using chloride concentration data is much higher than that would result from the precipitation excess (P - E) normalized to the surface area of the lakes. The higher dilution effect obtained using chloride data is most likely due to local surface inflow from the slopes of the lakes and, more importantly, to enhanced direct infiltration of precipitation on the areas adjacent to the lakes, where the upper part of the overburden has been removed by excavation, subsequently recharging the lakes.

6. Impact of the dredged lakes on the adjacent groundwater field

6.1. Based on saturation indices of carbonate minerals (SI) vs. P_{CO_2} analysis

In the mixing zones of the studied lakes, concentration of the Ca^{2+} and HCO_3^- ions and subsequently also the specific electrical conductivity considerably increased with diminishing lake water content (Fig. 8). In contrast, the change of Mg^{2+} concentration was insignificant. This is consistent with the faster dissolution kinetics of calcite compared to that of dolomite with the supply of CO_2 from the soil zone. Figure 9 exemplifies the systematic change of the saturation state of calcite and dolomite in the mixing zone. Apparently, $\text{SI}_{\text{calcite}}$ and $\text{SI}_{\text{dolomite}}$ decreased while P_{CO_2} increased with diminishing influence from the dredged lakes. The reported mean values are within an error of 0.02–0.06 for $\text{SI}_{\text{calcite}}$, 0.04–0.12 for $\text{SI}_{\text{dolomite}}$ and 0.02–0.06 for P_{CO_2} . The systematic change in chemical composition is clearly recognised along the main axis of the mixing zone from SB7 to BL7 in the Schwarzl Lake system and from S4 to Wz75 in the Weizelsdorfer Lake system. Beyond BL7 and Wz75, where the lake water content was less than 60 % and 70 %, respectively, the variation is less evident.

6.2. Based on $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data

Equilibrium and non-equilibrium isotope fractionation processes during evaporation lead to the enrichment of the heavy isotopes ^2H and ^{18}O in lake water. The degree of the evaporative enrichment is determined by meteorological variables such as relative air humidity over the lake and surface temperature of the lake, and the ratio of evaporation to inflow (R. GONFIANTINI, 1986, A. ZUBER, 1983, B. YEHDEGHO et al., 1997). Evaporative enrichment signature of stable isotopes is of major importance for the determination of the impact of the lakes on the downgradient groundwater field. This is particularly

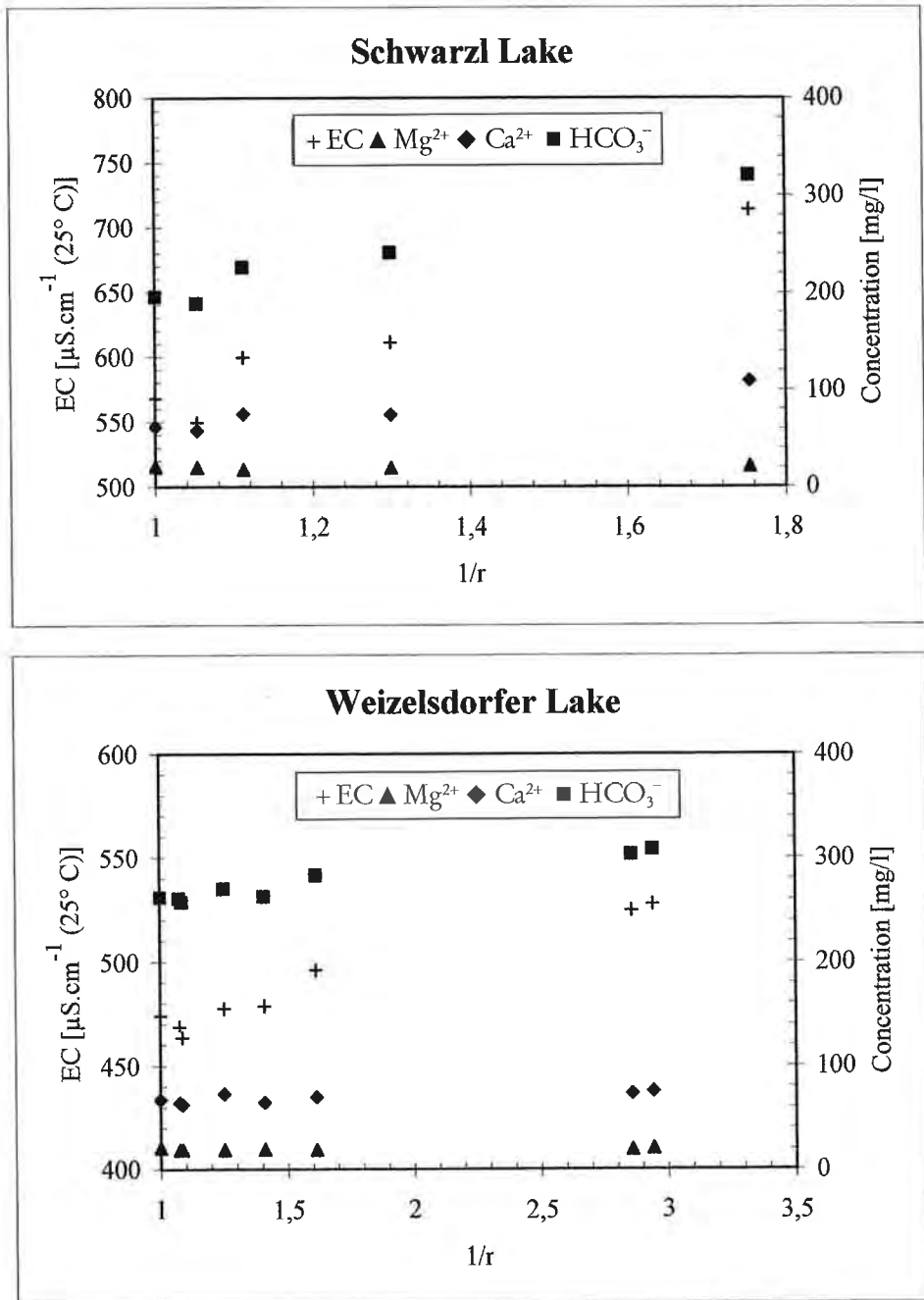


Fig. 8: Change of specific electrical conductivity (EC), Ca²⁺, Mg²⁺ and HCO₃⁻ concentration with decreasing lake water content in the mixing zones of the studied lakes.
 Zunahme der elektrischen Leitfähigkeit (EC), Ca²⁺-Mg²⁺- und HCO₃⁻-Konzentration mit der Abnahme des Seewassergehaltes in den Grundwassermessstellen in der Mischungszone der untersuchten Baggerseen.

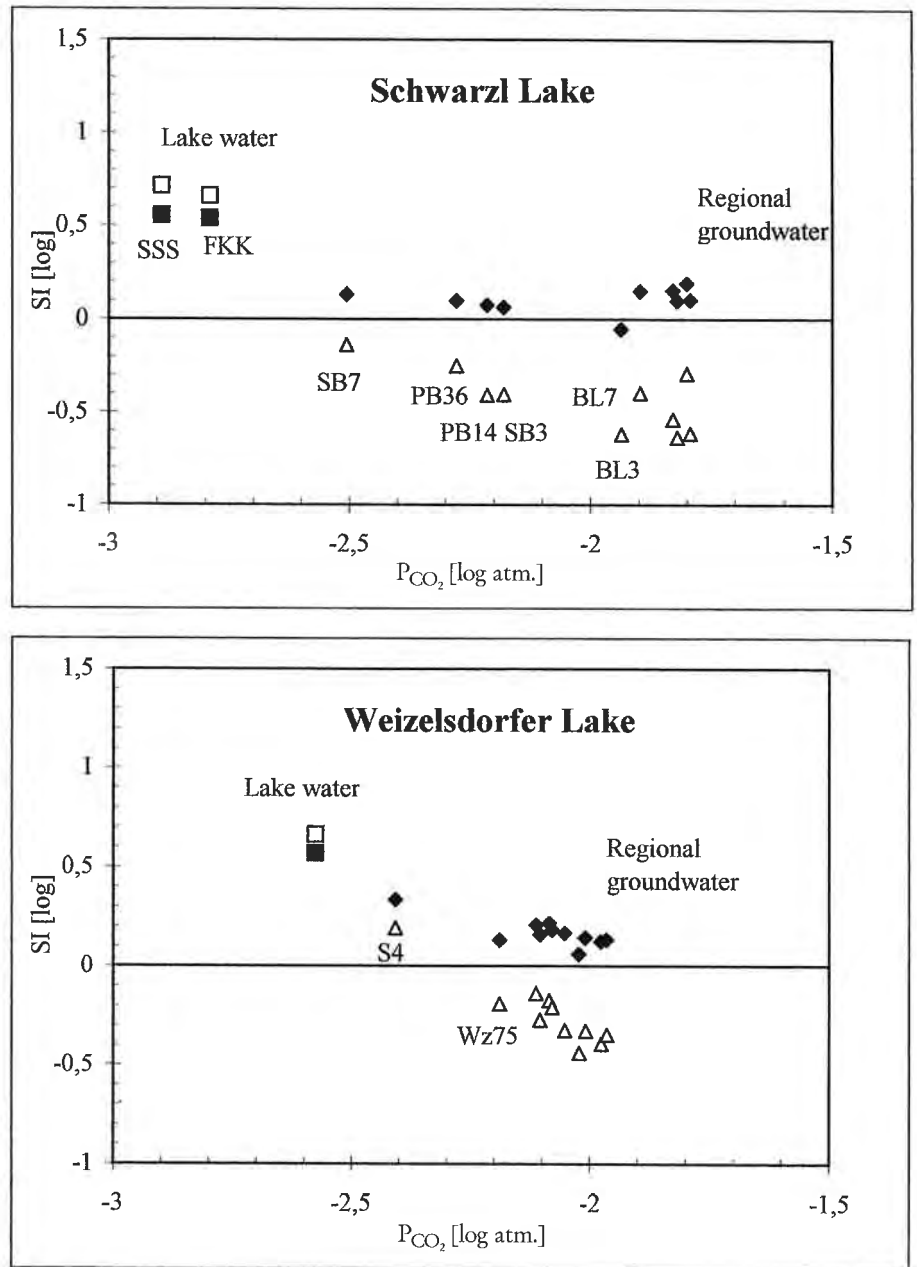


Fig. 9: Variability of the average $SI_{calcite}$ and $SI_{dolomite}$ vs. P_{CO_2} in the dredged lakes and adjacent groundwater. ■ denotes $SI_{calcite}$ vs. P_{CO_2} and □ $SI_{dolomite}$ vs. P_{CO_2} data points from the lakes; ◆ denotes $SI_{calcite}$ vs. P_{CO_2} and △ $SI_{dolomite}$ vs. P_{CO_2} data points from the observation wells in the mixing zones of the lakes.

$SI_{calcite}$ and $SI_{dolomite}$ vs. P_{CO_2} in den Baggerseen und im umliegenden Grundwasser. Symbole: ■ $SI_{calcite}$ vs. P_{CO_2} und □ $SI_{dolomite}$ vs. P_{CO_2} des Seewassers; ◆ $SI_{calcite}$ vs. P_{CO_2} und △ $SI_{dolomite}$ vs. P_{CO_2} des Grundwassers in der Mischungszone.

useful when assessing the vulnerability of wells situated in the mixing zone that may result from the gradual deterioration of the lake quality and accidental pollution of the lakes.

For this purpose, the lake water content in the wells downgradient of the investigated lakes was calculated from deuterium and oxygen-18 data, using the simple mixing equation $r = (\delta_m - \delta_i) / (\delta_L - \delta_i) \times 100$, where r is lake water content in % for the sample collected from the well; δ_m , δ_i and δ_L denote isotope content of the groundwater sample from the well located in the mixing zone, vertical infiltration component and lake water, respectively. In the wells situated in the mixing zone, lake water content varied with distance from the lake and relative position with respect to the main axis of the mixing zone.

In the Schwarzl Lake area, the lake water content in the wells SB6, SB7, PB13, PB14 and BL3 was > 90 %, in BL2 and SB3 approximately 80–90 %, BL7 approximately 60 %, BL26 approximately 40 % and PB21 and BL25 approximately 10 %. In the Weizelsdorfer Lake area, the lake water content in the wells S4 and S5 is > 90 %, S3, S7 and Wz75 approximately 70–80 %, S8 approximately 60 %, S10, Ho40 and Ho50 approximately 30–40 % and S6 < 10 %.

Mean δ values from the investigated lakes and the samples collected from selected observation wells in the adjacent groundwater fields have been plotted on the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ scatter diagram (Fig. 10). The local meteoric water line for Graz, which is located approximately 13 km in the NE of the study area, was determined using the long-term (1981 to 1995) monthly stable isotope content of precipitation.

Isotopic content of the water samples from the wells PB33, SB1 and SB5 represented the groundwater inflow to the Schwarzl Lake. As a result, the data points from these wells lay very close to the cross-point between the LMWL (Local Meteoric Water Line) and the mixing line. Whereas the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ data point of precipitation for 1991 fell slightly off the LMWL.

Owing to the strong enrichment of ^2H and ^{18}O in the Schwarzl Lake, the data points of the observation wells influenced by the lake lay on a well defined mixing line. This line was defined by the end-points of the average isotopic composition of the Schwarzl Lake (SSS in the diagram denoting the Sportler Lake) and of the groundwater inflow unaltered by the evaporation signal from the lake.

From the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ scatter diagram, it can be generalized that the higher the lake water content in the observation wells located in the mixing zone of the lakes, the closer the data points lie to the δ values of the dredged lakes. For example, the data points of the wells that contained > 90 % lake water (SB7, BL3 and PB14) lay very close to the δ values of the lake, whereas the data points from the wells that contained a small fraction of lake water (e.g. BL26) fell close to the cross-point with the LMWL.

Based on 1991 isotope data (Tab. 2), the isotopic enrichment of ^2H and ^{18}O was appropriately as high as 11 % and 20 % of the isotopic composition of the groundwater inflow to the Schwarzl Lake. This comparatively higher enrichment of the heavy stable isotopes in this lake was mainly the effect of the successive evaporation of water in the north to south aligned lake basins (B. YEHDEGHO et al., 1997). On the other hand, the isotopic enrichment of deuterium and oxygen-18 was relatively small in the Weizelsdorfer Lake, only approximately 5 % and 6 %, respectively. Consequently, even the wells that contained a higher fraction of lake water, symbolized as an open square in Fig. 10 did not show a significant positive shift of $\delta^{18}\text{O}$. The data points of the remaining observation wells and precipitation from 1991 fell on the GMWL (Global Meteoric Water Line).

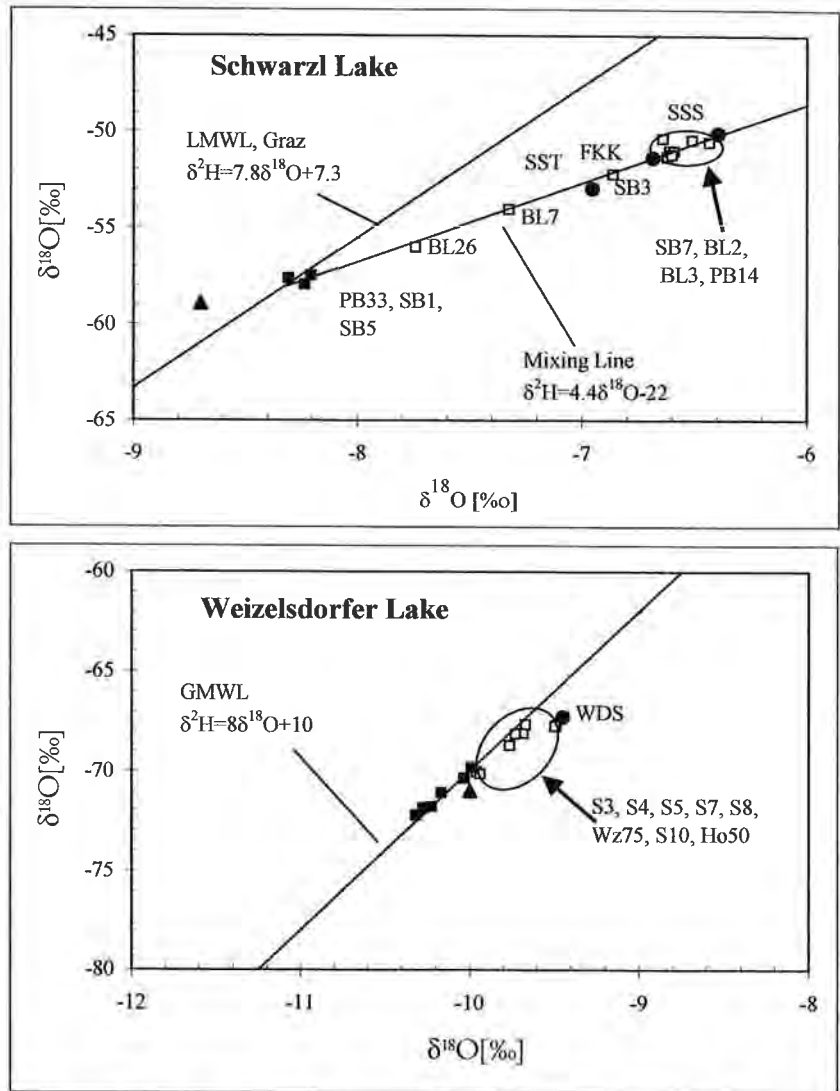


Fig. 10: $\delta^2\text{H}$ vs. $\delta^{18}\text{O}$ scatter diagram for the studied dredged lake systems and the adjacent groundwater fields. SST denotes STUAG Lake, SSS Sportler Lake, FKK FKK Lake of the Schwarzl Lake system and WDS the Weizelsdorfer Lake; LMWL is the Local Meteoric Water Line, GMWL the Global Meteoric Water Line; ● denotes mean isotopic composition of dredged lakes, ■ isotopic composition of groundwater samples collected from observation wells not influenced by lake water, □ isotopic composition of the samples collected from observation wells in the mixing zones and ▲ weighted mean isotopic composition of precipitation for 1991.

$\delta^2\text{H}$ - $\delta^{18}\text{O}$ -Relation für die untersuchten Baggerseen und das umliegende Grundwasser. Abkürzungen: SST STUAG See, SSS Sportlersee und FKK FKK See (Schwarzl Baggerseen) und WDS Weizelsdorfersee; LMWL örtliche Niederschlagsgerade, GMWL globale Niederschlagsgerade; Symbole: ● Isotopengehalt der Baggerseen, ■ Isotopengehalt der Grundwasserproben im Zustrombereich (unbeeinflusst vom Seewasser), □ Isotopengehalt der Grundwasserproben der Messstellen in der Mischungszone und ▲ Isotopengehalt vom Niederschlag für 1991 (gewichtet).

7. Discussion and conclusions

Both the Schwarzl and the Weizelsdorfer Lakes are typical through-flow systems, whose water and solute budgets are primarily controlled by the transient groundwater. Their hydrochemical composition was considerably modified through dilution and hydrogeochemical as well as hydrobiochemical reactions in the dredged lakes. Dilution effect was estimated using the decrease in chloride concentration as a reference. Based on the chloride data from 1991, the decrease in concentration due to dilution accounted for 25 % in the Schwarzl Lake and 11 % in the Weizelsdorfer Lake. By subtracting the dilution effect from the net annual chemical balance, the change in concentration of the dissolved solutes pertinent to geochemical and biochemical reactions in the lakes (in-lake source/sink function) was then obtained. Although the impact of the in-lake source/sink function on the various chemical components differed in magnitude, a similar pattern of chemical change was obtained for both lake systems. A decrease in the concentration of Na^+ , Ca^{2+} , HCO_3^- , NO_3^- and SiO_2 , and a rise in the concentration of Mg^{2+} , SO_4^{2-} and K^+ ions was observed (cf. tab. 5 last column). Carbonate mineral dissolution/precipitation reactions and biological uptake of biophilic species are the predominant mechanisms that regulated the hydrochemical composition of the studied lakes. The former controlled the distribution of Ca^{2+} , Mg^{2+} and HCO_3^- and the later the concentration of NO_3^- and SiO_2 .

As a result of calcite mineral precipitation induced by P_{CO_2} drop, the concentration of Ca^{2+} and HCO_3^- decreased by approximately 18 % and 14 % in the Schwarzl Lake, and by only 4 % and 5 % in the Weizelsdorfer Lake (Tab. 4 and 5). In both lakes, a higher degree of supersaturation was maintained with respect to calcite and exhibited a distinct seasonality. Higher $\text{SI}_{\text{calcite}}$ values were obtained in summer (Fig. 7), corresponding well with a lower concentration of Ca^{2+} and HCO_3^- ions. This suggests enhanced removal of the ions by precipitation as a result of thermal degassing of CO_2 . Conversely, a reversed phenomenon was observed during winter, i.e. a low supersaturation with respect to calcite and a high Ca^{2+} and HCO_3^- concentration. Mg^{2+} exhibited a different distribution pattern than Ca^{2+} and HCO_3^- . Compared to the composition of the groundwater inflow to the lakes, its concentration rose by approximately 58 % in the Schwarzl Lake and by about 18 % in the Weizelsdorfer Lake. This increase was most probably caused by the release of Mg^{2+} by incongruent dissolution of dolomite (a condition in which calcite is precipitated while dolomite is dissolved). Most of the time, lake water samples were supersaturated with respect to dolomite and the saturation indices showed a much stronger seasonality than the one of calcite; from spring to autumn $\text{SI}_{\text{dolomite}}$ surpassed $\text{SI}_{\text{calcite}}$ and vice versa during winter. This can be explained by the variable temperature effect on the solubility of calcite and dolomite. Thermodynamic data indicates a relatively enhanced solubility of dolomite at lower solution temperatures. However, the concentration of Mg^{2+} in the lakes did not vary significantly with time. According to R. A. FREEZE & J. A. CHERRY (1979), dolomite precipitation reaction is so sluggish that the ions involved continue to remain in solution for long periods of time with little or no dolomite precipitation. Also, most likely for the aforementioned reason, the average saturation index of dolomite surpassed that of calcite in the lakes (Fig. 9). The calculated equilibrium partial pressures of CO_2 were approximately $10^{-2.9}$ atm. for the Schwarzl Lake and $10^{-2.6}$ atm. for the Weizelsdorfer Lake. Accordingly, these values were lower than the P_{CO_2} content in the respective groundwater inflow by about an order and one fourth of magnitude.

Mainly due to biological uptake, concentration of NO_3^- and SiO_2 was depleted in the lakes. Occurrence of a large number of phytoplankton, including diatoms, zooplankton species, and bacteria as well as macrozoobenthos was reported (BMFLF, 1995). Photosynthesizing plants in aquatic environments require nitrogen, which they may absorb through roots in the bottom sediment or may assimilate directly from water. Certain algal species (diatoms) extract silica from the water in which they grow to form incrustations (J. D. HEM, 1985). Compared to the concentration in the groundwater inflow, the retention of NO_3^- reached approximately 35 % in the Schwarzl Lake and only about 10 % in the Weizelsdorfer Lake. Whereas the retention of SiO_2 in the lakes was even higher, approximately 48 % and 41 % of the concentration in the subsurface inflow, appropriately.

Sorption and ion exchange reactions in the fine sediments drifting from the aquifer and organic matter accumulated in the lakes were probably responsible for the change in Na^+ and K^+ concentration. Na^+ decreased only by 5 % and 7 %, while K^+ increased by 62 % and 50 % compared to the concentration in the groundwater entering into the Schwarzl Lake and the Weizelsdorfer Lake, appropriately. However, it must be emphasized that K^+ content was very low ($< 4 \text{ mg/l}$) in the studied systems.

Sulfate accumulated to a considerable extent in the dredged lakes; it reached, compared to the concentration in the subsurface inflows, approximately 78 % in the Schwarzl Lake and 25 % in the Weizelsdorfer Lake. The contribution of precipitation to the SO_4^{2-} budget in the lakes was very minor (Tab. 5). Sulfate measurements performed in different parts of Austria revealed that the contribution of dryfall can be slightly higher or comparable to the input from precipitation (M. F. KALINA, personal communication). This means that the input from dry deposition is equally insignificant and cannot be the cause for the large sulfate build-up observed in the lakes. Thus, further detailed investigation is needed to fully understand the sources of the SO_4^{2-} accumulation in the dredged lakes.

Comparatively, a strong hydrochemical change and enrichment in heavy stable isotopes has been observed in the Schwarzl Lake system. This can be explained by the special arrangement of the lakes in the shallow groundwater flow system. It can be derived from the pattern of the groundwater contour lines (Fig. 1) that the Schwarzl Lake is recharged by groundwater inflow and seepage from the upstream STUAG Lake. This suggests that the hydrochemical change observed in the Schwarzl Lake also integrates the dilution and in-lake source/sink effects of chemical components in the upstream lakes (STUAG and Samitz Lakes), for which unfortunately no hydrochemical data was available. The successive evaporation in the dredged lakes that are N-S aligned was also the main cause for the strong enrichment of ^2H and ^{18}O in the Schwarzl Lake, reaching as high as 11 % and 20 % of the isotopic composition of the groundwater inflow, accordingly. On the other hand, the hydrochemical changes and the isotopic enrichment was comparatively small in the Weizelsdorfer Lake; the ^2H and ^{18}O enrichment was only approximately 5 % and 6 % of the isotopic composition of groundwater inflow, respectively.

A systematic change in chemical composition of groundwater was observed in the mixing zone with decreasing impact from the lakes. Figure 8 shows the increase of the specific electrical conductivity and the concentration of Ca^{2+} and HCO_3^- in groundwater with increasing $1/r$ (reciprocal of the lake water content in the wells). This is mainly associated with the faster calcite dissolution. It should be noted that the change of concentration of Mg^{2+} and the remaining chemical species (Na^+ , K^+ , NO_3^- , SO_4^{2-} and SiO_2) was negligibly small. On the other hand, the pH sank with decreasing influence

from the dredged lakes as a consequence of the increased supply of CO_2 from the soil zone. The variation of chemical composition was particularly evident from the saturation indices of the carbonate minerals and P_{CO_2} . As shown in fig. 9, $\text{SI}_{\text{calcite}}$ and $\text{SI}_{\text{dolomite}}$ decreased with diminishing impact from the lakes, while P_{CO_2} increased in the groundwater samples collected from wells in the mixing zone. In general, the systems tended to attain the saturation state of calcite and dolomite minerals and P_{CO_2} of the regional groundwater system.

The estimate of the chemical mass flux for the studied lakes is probably accurate to within 20–30 %. The certainty of the calculated chemical mass balance primarily depends on the accuracy of the lake water budget and the chemical data used. Therefore, to obtain reliable results the hydrochemical and isotopic composition of the lake system under investigation has to be monitored rather extensively at monthly intervals for at least one year. Furthermore, the modified chemical characteristics, particularly SI of calcite and dolomite and P_{CO_2} , as well as the evaporative signature on the stable isotopes (deuterium and oxygen-18), allowed the evaluation of the impact of dredged lakes on the downgradient groundwater field. However, when the lake water content in the wells was low (< 60–70 %), the influence of the dredged lakes was hardly recognizable from hydrochemical data. This emphasizes the advantage of the stable isotopes as conservative tracers over chemical parameters in determining the impact of evaporated lakes on adjacent downgradient groundwater fields, particularly the mixing zones.

Summary

A detailed hydrochemical and isotopic study performed during 1990 to 1993 allowed the determination of the impact of the formation of dredged lakes on the hydrochemical and isotopic composition of the shallow groundwater fields in the Schwarzl Lake and Weizelsdorfer Lake areas. The knowledge of the resulting hydrogeochemical and biochemical changes due to the formation of dredged lakes is not only of importance in taking precautionary measures to protect the shallow aquifers from pollution, it also provides a basis for decisions regarding the location of future projects for sand and gravel mining in shallow groundwater fields, particularly when the aquifer is exploited for water supply.

The Schwarzl and the Weizelsdorfer Lakes are typical through-flow systems, whose water and solute budgets are primarily controlled by transient groundwater. Through-flow rates, estimated with the help of stable isotopes, deuterium and oxygen-18, together with the hydrochemical data from 1991 allowed the quantification of the chemical mass budget of the major chemical species within 20–30 % of uncertainty. Dilution and in-lake source/sink processes altered the hydrochemical composition of studied lakes considerably. The dilution effect (due to precipitation falling direct on the surface of the lakes) was approximated at 25 % and 11 % of the inputs to the Schwarzl Lake and the Weizelsdorfer Lake, respectively, using chloride concentration data. The change in concentration of the major dissolved solutes resulting from in-lake source/sink function (net annual budget minus dilution effect) was variable. However, the general change pattern was a decrease of Na^+ , Ca^{2+} , HCO_3^- , NO_3^- and SiO_2 components and an increase in Mg^{2+} , SO_4^{2-} and K^+ concentrations in both lakes.

Dissolution/precipitation reactions of carbonate minerals and biological uptake of biophilic elements were the main contributors to the in-lake source/sink function. The

former caused a substantial change in Ca^{2+} , Mg^{2+} and HCO_3^- concentrations. Precipitation of calcite mineral induced by P_{CO_2} drop in the lakes resulted in the decrease of Ca^{2+} and HCO_3^- concentration in lake water. On the other hand, incongruent dolomite dissolution reaction resulted in a considerable increase of Mg^{2+} concentration in the lakes. Biological uptake in lake water caused a substantial decrease in NO_3^- and SiO_2 concentration.

Chemical and isotopic modification of lake water is very important indicator for tracing the influence of dredged lakes on the adjacent groundwater field. Particularly, $\text{SI}_{\text{calcite}}$ and $\text{SI}_{\text{dolomite}}$ together with P_{CO_2} and the evaporative signature on $\delta^2\text{H}$ and $\delta^{18}\text{O}$ prove to be very useful tools in determining the impact of dredged lakes on the mixing zones, i.e. in identifying the wells containing lake water and to quantify the mixing ratio. From chemical data, only the wells that contain a large fraction of lake water (> 60–70 %) could be identified. This fact shows the advantage of the stable isotopes as conservative tracers over chemical parameters in determining the impact of evaporated lakes on the downgradient groundwater fields.

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Zusammenfassung

Am Schwarzl- und Weizelsdorfer See wurden in den Jahren 1990 bis 1993 detaillierte hydrochemische und isotopenhydrologische Untersuchungen durchgeführt, um die Auswirkungen von Baggerseen auf das unterströmige Grundwasser zu erkunden.

Die Kenntnis der hydro- und biochemischen Veränderungen, die durch die Schaffung eines Baggersees auftreten können, ist nicht nur für die vorausgehenden Beweissicherungsmaßnahmen zum Schutz des seichtliegenden Aquifers wichtig, sondern bildet auch die Grundlage für Entscheidungen bei zukünftigen Kiesentnahmen im seichtliegenden Grundwasserfeld, besonders wenn der Aquifer ein Hoffungsgebiet für eine öffentliche Wasserversorgung darstellt.

Der Schwarzl und Weizelsdorfer See sind typische Beispiele für Baggerseen, deren Wasser- und Stoffhaushalt vor allem vom durchströmenden Grundwasser gesteuert wird. Die Abschätzung der Durchflußraten mit Hilfe der stabilen Isotope Deuterium und Sauerstoff-18 erlaubt, zusammen mit den hydrochemischen Daten des Jahres 1991, eine Quantifizierung der Stoffbilanz bis zu einem Unsicherheitsfaktor von ± 20 –30 %.

Lösungserscheinungen oder Ausfällungen und biologische Umsetzungen tragen wesentlich zu Zu- bzw. Abnahmeprozessen im Seewasserchemismus bei. Sie verursachen eine deutliche Veränderung der Ionenkonzentration bei Ca^{2+} , Mg^{2+} und HCO_3^- . Ausfällungen von Calcit durch die Entweichung von gelöstem CO_2 bewirken zudem eine Abnahme des Ca^{2+} - und HCO_3^- -Gehaltes im Seewasser. Auf der anderen Seite kommt es durch Lösungserscheinungen zu einer deutlichen Zunahme der Mg^{2+} -Konzentration im See. Biologische Umsetzungen führen zu einer Verringerung der Konzentration bei den Parametern NO_3^- und SiO_2 .

Neben der chemischen Zusammensetzung des Seewassers sind vor allem die stabilen Isotope als konservative Tracer zur Abgrenzung des Einflßbereiches der Baggerseen auf ihr umgebendes Grundwasserfeld von Bedeutung. So konnten jene Brunnen, die auch nur geringfügig mit Seewasser kontaminiert waren, identifiziert und ihr Mischungsverhältnis quantifiziert werden. Mit Hilfe der chemischen Signatur waren nur jene Brunnen erkennbar, die mindestens einen Anteil von 60–70 % Seewasser hatten.

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