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Estimation of erosion and sediment yield by volume measurements on a lacustrine river delta

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ABSTRACT In 1811 the River Linth, which drains 600 km^2 of the Glarus Alps (Switzerland), was diverted by the construction of a canal into a lake (the Walensee), where it has built a rapidly growing delta cone. The increase in deposited sediment volume was measured by different bathymetric surveys (1849, 1860, 1911, 1931, 1979) and gives a valuable estimate of erosion in the drainage area. Whereas the wire sounding method was used until 1931, the 1979 survey was performed by a largely automated survey system based on digital terrain models established by high resolution echo-sounding combined with laser-guided and computerized polar positioning. Since the last survey (1931) the increase in the delta volume was about 6.5 x 10^6 m^3 in 48 years thus implying an average annual lowering of the drainage area by 0.23 mm. Compared with the earlier survey period (1911-1931: 0.17 mm $year^{-1}$), this indicates increased erosion, probably as a result of unusual floods. Based on these data, a simple model is used to predict erosion in the drainage area of the River Linth.

INTRODUCTION

The Lake of Walenstadt (Walensee) is a long and narrow peri-alpine lake with a maximum depth of 145 m (Fig.1). The drainage basin is 1061 km^2 in extent, and the bedrock is mainly sedimentary. The terrain is rugged with high peaks over 3000 m in altitude and partly covered by glaciers. The climate is temperate and humid. Altogether 35 rivers and streams flow into the lake. However, the River Linth, which drains mainly the Glarus Alps (c. 600 km^2), is by far the largest and contributes about 70% of total water input to the lake.

Before 1811 the River Linth did not flow into the Walensee but meandered across the so-called Linth plain before it reached Lake Zürich, 35 km to the west. During the eighteenth century floods were frequent, the ground was marshy and the population suffered from endemic malaria. In 1811 the River Linth was diverted into the Walensee through the construction of a canal. Since that time the sediments of the river have been deposited in the lake and the plain has been free of inundation.

The diversion of the river into the lake led to a doubling of the lake's drainage area and therefore a drastic change in the sediment

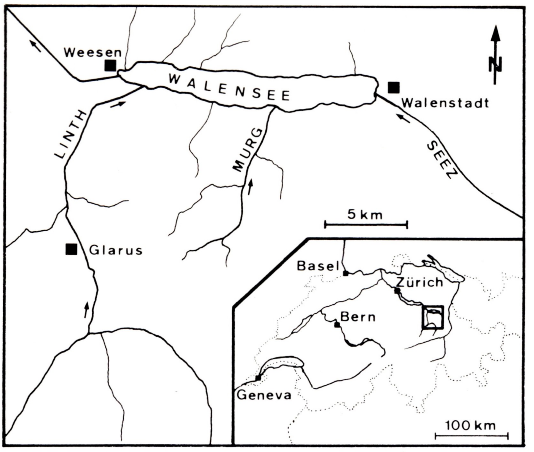

FIG.1 Index map: Lake of Walenstadt (Walensee) in the northeastern part of Switzerland.

regime. The addition of the Linth sediments resulted in a rapidly growing delta and an increase in the sedimentation rate in the central lake basin, with a marked change of sedimentary facies occurring in 1811. In sediment cores from the western part of the basin, fine grained reddish-brown muds are overlain by a sequence of grey coarse-graded sands (Lambert, 1978). This time marker enables us to determine the sedimentation *rates* since 1811 at the sample sites but not the *volume* of the deposited delta material.

THE DELTA OF THE RIVER LINTH

The rapidly growing cone of detritus at the mouth of the lake's man-made main tributary has been repeatedly surveyed since 1811. Fig.2 shows the different stages of delta progradation in a southwest-northeast profile, which is the direction of the inflow canal. However, only the surveys from 1911, 1931 and 1979 were carried out with an accuracy that enables estimation of volume differences due to sediment input and/or erosion.

After 1931, no further survey took place until 1979 when the

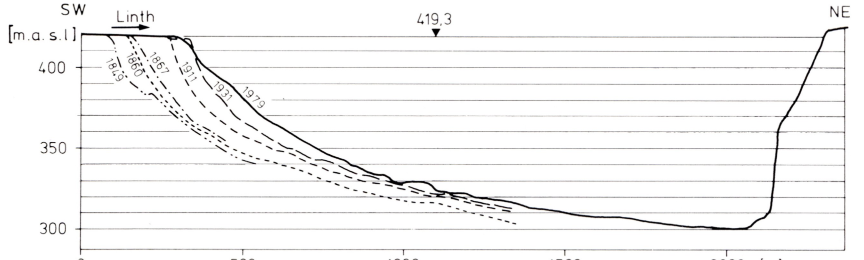

FIG.2 Different stages in the evolution of the Linth delta shown by a southwest-northeast profile (based on Collet & Stumpf (1916) and Eidgenössisches Amt für Wasserwirtschaft (1934).

Laboratory of Hydraulics, Hydrology and Glaciology initiated a new bathymetric mapping of the Linth delta as part of a research project on deltaic sedimentation and lacustrine turbidity currents. Whereas the previous surveys were performed by time-consuming wire soundings which are very susceptible to errors, the 1979 survey was performed using a modern bathymetric mapping system developed by the Swiss engineer Dr. Robert A.Schlund.

DESCRIPTION OF THE SURVEY METHOD

The survey system is based on the principle of polar positioning combined with high resolution echo-sounding. The survey vessel (a 9.2 m coastal cruiser) moves on predetermined profiles which are marked by a laser beam coupled with the theodolite (Wild T2) of the land station.

The distance between the ship's antenna, which is located exactly above the transducer of the echo-sounder, and the antenna of the land station is measured continuously by the Krupp-Atlas (Ralog) radio navigation system. The distances measured are digitally displayed and are available on call for further processing in the on-board computer together with the values of the corresponding water depth.

Depth sounding is performed using the Krupp-Atlas high resolution echo-sounder DESO. Two ultrasonic frequencies can be run simultaneously (33 kHz and 210 kHz). Using a special test transducer the actual velocity of sound propagation can be established with an accuracy of about 2 m s^{-1} in order to calibrate the echo-sounder.

Combined with the continuous distance measurement, the paper speed of the echograph is proportional to the speed of the vessel, thus the horizontal scale of the depth profile is true to scale.

The computing system is linked on-line to the measuring system from which it received the digital input. Data from the established digital terrain model of the lake bottom are stored on magnetic tape. Further processing to produce a contoured map is performed using an Olivetti P 652 office computer.

This largely automated system allows a rapid *and* precise survey of large areas (up to 200 ha day^{-1}), whereas several weeks were necessary to cover the same area during the previous surveys with wire soundings.

SEDIMENT YIELD AND EVOLUTION OF THE LINTH DELTA SINCE 1911

The volumetric evolution of the Linth delta since the 1911 survey is summarized in Table 1. Compared to the period 1911-1931, the average annual sediment input from 1931 to 1979 increased by about 8%. This slight increase is probably due to some unusual floods which occurred in 1939, 1944, 1953, 1963 and 1977, whereas between 1911 and 1931 only the 1922 flood was significant.

These floods usually generate turbidity underflows with velocities up to 50 cm s^{-1} (Lambert, 1979) and sediments may travel over long distances before being deposited in the deeper parts of the basin. As the largest amounts of sediments are transported into the lake during high flood stages, it is important that the survey perimeter is extended to the distal parts of the bottomset beds.

TABLE 1 Volumetric evolution of the Linth delta (in $10^6 m^3$)

	Survey period: 1911-1931	*1931-1979*
Measured increase in volume	*2.3*	*5.3*
Dredged material	*0.1*	*1.1*
Total	*2.4*	*6.4*
Average annual increase	*0.12*	*0.13*

EROSION OF THE DRAINAGE BASIN

Based on the sediment input from the River Linth between 1911 and 1931, Jäckli (1958) made an attempt to estimate the erosion of the drainage basin and hypothetically to extrapolate future erosion, using the simple assumption of exponential decay (Fig.3), i.e. that

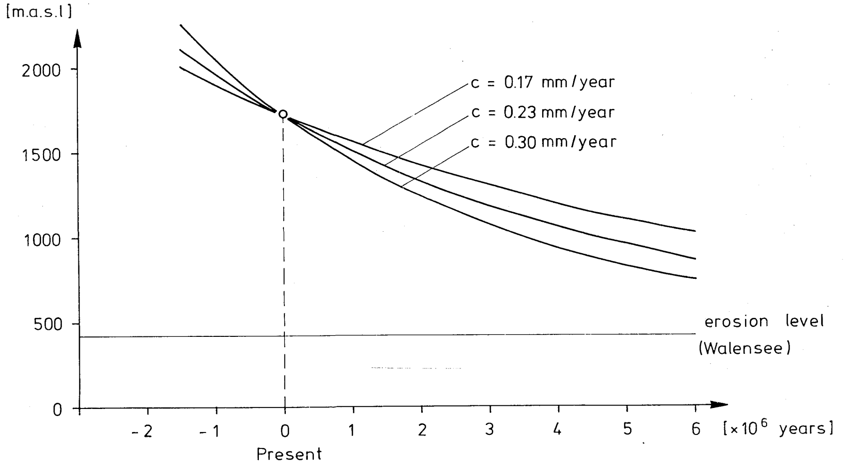

FIG.3 Hypothetical lowering of the drainage basin of the River Linth, based on delta surveys from 1911 to 1931 (erosion rate c = 0.17 mm year^{-1}) and from 1931 to 1979 (c = 0.23 mm year^{-1}). If chemical dissolution is taken into account for the 1931-1979 period the erosion rate is increased to c = 0.30 mm year^{-1}.

the erosion rate c is proportional to the initial mean altitude h_0 of the catchment area as a function of the time t. The mean altitude h_t of the catchment area at any time t may be found using the equation

$$h_t = h_o\ e^{-\lambda t} \qquad (1)$$

where $\lambda = c/h_o$ = erosion coefficient.

From the values in Table 1 it follows that between 1911 and 1931, the erosion was 227 $m^3 km^{-2} year^{-1}$, and therefore the annual lowering of the catchment area c = 0.17 mm $year^{-1}$. The corresponding values for the 1931-1979 period are 315 $m^3 km^{-2} year^{-1}$ and c = 0.23 mm $year^{-1}$. Based on the assumptions mentioned above, the corresponding erosion functions can be drawn according to equation (1) (Fig.3).

Considering the different survey methods and the different observation periods, both values obtained for the average annual erosion rate are surprisingly close together and rounded to one decimal digit they are identical. Therefore, we presume that this value reflects, reasonably well, the erosion rate of the drainage basin - at least as far as the fluvial transport of solid matter is concerned.

Indeed, this value does not take into account the transport of chemically dissolved matter which is certainly not negligible. According to measurements performed by the Water Supply Agency of Zürich, the concentration of dissolved matter at the mouth of the River Linth is about 120 mg l^{-1} on average over the last 10 years. As there are no significant changes in the concentration as a function of the water discharge (25 $m^3 s^{-1}$ on average), we can estimate the additional erosion of the drainage basin due to chemical dissolution at 60 $m^3 km^{-2} year^{-1}$ or an average lowering of 0.07 mm $year^{-1}$ (see Fig.3).

CONCLUSIONS

Periodic surveys of lacustrine river deltas can provide a reasonable estimate of sediment yield from a drainage basin. However, the hydrographic measuring accuracy should, at least, be equal to that obtainable by aerial photogrammetry. Special care should be taken that the distal parts of the bottomset are included in the survey, as sediments may travel over long distances as turbidity underflows, before being deposited far away from the river mouth. In order to estimate erosion rates of the drainage basin it is important to take into account the transport of chemically dissolved matter in addition to deltaic sedimentation.

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