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Sediment contamination in a river reservoir (Wettingen Reservoir, Switzerland): Present situation and history

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Key words: Reservoir, sediment contamination, Limmat river, Switzerland.

ABSTRACT

A reservoir located on the Limmat River down stream from Zürich has been investigated in order to determine the history of sediment contamination since 1930 - 1933, when the dam was built, and to evaluate risk for man and the environment.

Levels of contamination by heavy metals and nutrients are low at the beginning, but increase rapidly. High levels are registered from about 1960 to 1975. Recent surface sediments have low levels again. PCB and PAH concentrations are very high at the base of the sediments, but decrease rapidly upward. The main source of contamination is up stream, but local sources are identified as well.

The main risks for man and environment are linked to the uptake of contaminated sediment or surface water by organisms and to groundwater infiltration; further investigations are currently conducted.

ZUSAMMENFASSUNG

Der Wettinger Stausee entstand beim Bau des gleichnamigen Kraftwerkes in den Jahren 1930 – 33 an der Limmat unterhalb Zürich. In der vorliegenden Studie wurden Seesedimente bezüglich Kontamination untersucht und das Risiko für Mensch und Umwelt abgeschätzt.

Die Kontamination durch Schwermetalle und Nährstoffe ist in den älteren Schichten vorerst gering, steigt aber gegen oben rasch an. Die höchsten Werte stammen aus den Jahren 1960 bis 1975. In den jüngeren Oberflächenschichten sind die Konzentrationen wiederum gering. Gehalte an PCB und PAK sind in den tiefsten Schichten sehr hoch, nehmen dann aber rasch ab. Die Hauptquelle für die Sedimentkontamination liegt im Oberlauf der Limmat; lokale Quellen können aber auch identifiziert werden.

Die Risiken für Mensch und Umwelt betreffen sowohl die Aufnahme von Schadstoffen aus dem Sediment und Oberflächenwasser durch Organismen, als auch Grundwasserinfiltration; weitere Untersuchungen hierzu sind im Gange.

1.- Introduction

Hydroelectric plants were constructed in Switzerland along rivers and streams at the end of the 19th and especially in the early 20th centuries (DHS 2001).

Geochemical analysis of sediment cores from the Klingnau reservoir (lower Aare river, Vernet et al. 1989) provided for the first time a record of heavy metal contamination from about 1950 to the present. This analysis showed that reservoirs had accumulated considerable amounts of contaminated sediments in the past.

In the frame of a project for modernising hydroelectric equipment and renewing the corresponding water conces-

sion, an environmental impact study has been carried out from 1997 to 2001 on the Wettingen reservoir of the Limmat River, about 20 km down stream of the lake and city of Zürich (Fig. 1). An 18-m high dam, which exists since its construction in 1930 – 1933, forms this 7-km long reservoir. The Limmat River has a mean annual runoff of 102 m³/sec in the town of Baden, and a maximum flood runoff of 660 m³/sec (SHGN 1999, p. 236). It is fed mainly by the rather regular outflow of Lake Zürich and by the Sihl River, which is within an alpine drainage basin with high flood and sediment discharge. Small local rivers enter the Limmat River or the reservoir between

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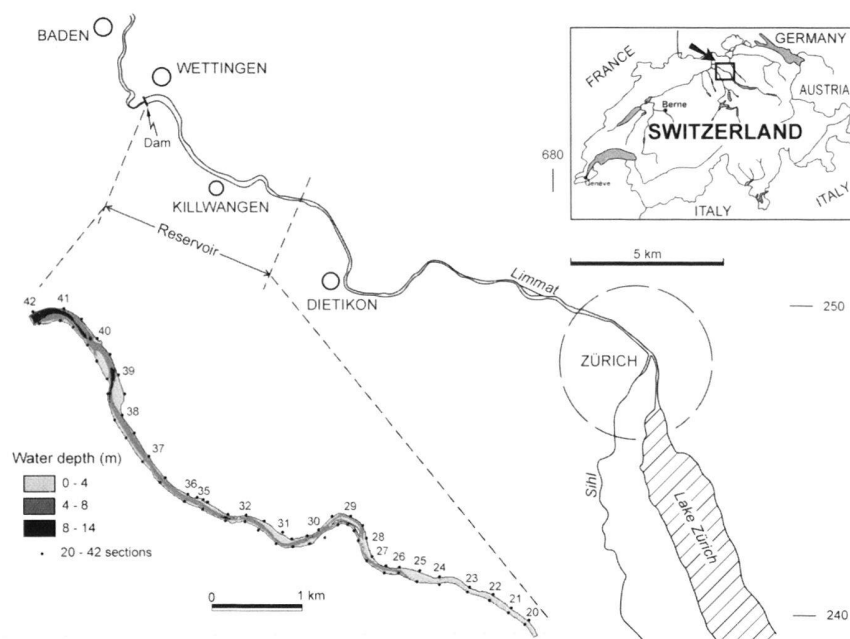


Fig. 1. Location and bathymetric map of the Wettingen reservoir

Zürich and the Wettingen dam. Urban and industrial waste water from the city of Zürich and its agglomeration were first discharged directly into the river, but are now collected and treated.

As part of an environmental impact assessment, the Institute Forel – team studied the sedimentary record of the reservoir, qualitatively and quantitatively, and assessed the environmental risk. The study included bathymetric mapping, sedimentological and geochemical analysis of surface sediments (grab samples) and sediment cores, and toxicological investigations. Research was carried out by an interdisciplinary team, and monitoring and further research is continuing. This paper summarises results related to the sediment record.

2.- Methods

Detailed maps of the reservoir basin morphology were produced with a MARIMATEC 200 kHz echosounder, DGPS positioning and computer-based plotting (Fig. 1). Historical data for the construction of the sediment model (Fig. 2) stem from periodic measurements of river sections by the hydroelectric company in 1932, 1935 – 1937, 1951, 1958 and 1988. Seismic investigations were not successful due to high gas content of the sediment.

Volume magnetic susceptibility on sediment cores was measured with a BARTINGTON MS 2-Susceptibility meter (Thompson & Oldfield 1986). Water content was determined by drying of the sediment and grain size on grab sam-

ples and sediment cores was measured with a Laser Coulter 100 (Loizeau et al. 1994). ^{137}Cs - radioisotope measurements have been carried out on sediment cores with a "PGT Ge (Li) Well type detector" (Dominik et al. 1987).

The following compounds were measured in surface sediment samples (grab samples) and sediment cores: Hydrocarbon, AOX (Adsorbable halogenated hydrocarbons), PCB (Polychlorinated Biphenyls), PAH (Polychlorinated aromatic hydrocarbons), organic carbon (C), organic nitrogen (N), total phosphorous (P) and heavy metals (FOREL 1998). Before extraction, all sediments were sieved and only the silt- and clay-fractions (< 63 microns) were considered. For metal determinations, extractions were made according to VSBo (1986) and VBBo (1998), using 2M - HNO_3 . Element analysis was performed using ICP-MS and ICP-OES techniques. Cold vapour extraction and analysis of mercury follows Hatch & Ott (1968), whereas phosphorous analysis and organic carbon analysis use the methodology discussed by Williams et al. (1980) and by Gaudette et al. (1974) respectively. Organic nitrogen was analysed at the Laboratory for Agriculture at Lullier following Kjeldahl (1883) and hydrocarbon, AOX, PCB and PAH analysis were performed at the Institute Bachema (Schlieren) using infrared, coulometric and gas chromatographic techniques.

3. - Reservoir morphology and sedimentology

The original river bed is a forced meandering channel, eroded

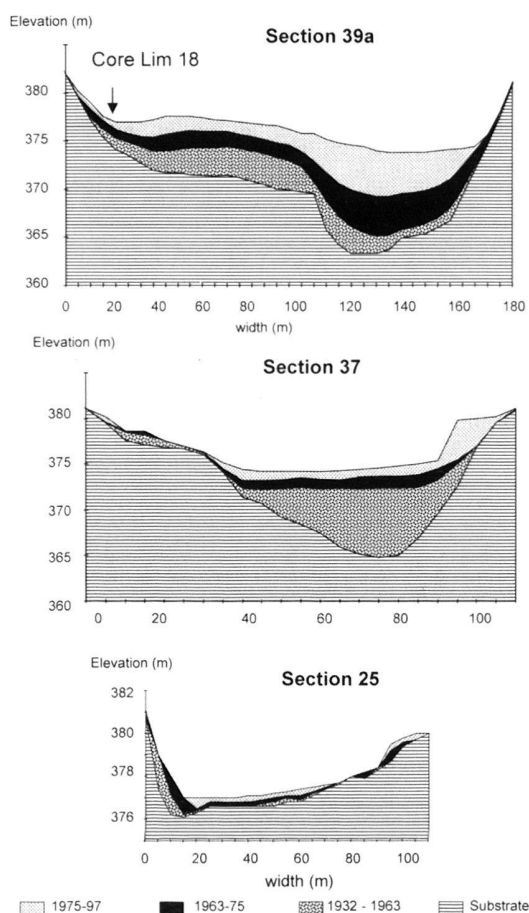


Fig. 2. Cross-sections showing the lake profile and sediment fill in the upper, central and lower reservoir basin (for location see Fig. 1). Time lines are from former measurements of lake sections (IBA personnel communication) and from dating by Cs137.

into fluvio-glacial deposits of the last ice-age and crossing a frontal moraine ridge near the city of Würenlos. The dam is located on Molasse bedrock.

Figure 2 represents characteristic, simplified cross-sections from the upper (section 25), middle (section 37) and lower parts (section 39a) of the reservoir. In the whole reservoir, sedimentation occurs in the deep central part of the basin and as point bars in the meanders. As a consequence of point bar deposition the central channel of the river shifts toward the periphery, and sinuosity, therefore, increases with respect to the original riverbed.

In the upper part of the reservoir, today's section represents a new equilibrium, and erosion and redeposition may occur during high runoff. In the central part, sedimentation is still very dynamic and erosion may occur by stream currents as

well as by slumping. In the lower part of the reservoir, sedimentation occurs in all parts of the basin.

Channel floor topography in all parts of the reservoir includes depositional waves and scour pools, and is, therefore, quite irregular.

Bar sediments range from silty sand to sandy silt, depending on the water depth. This effect is best illustrated by sediment core Lim 18.3, which is from a bar shown in section 39a (Fig. 2). Mean grain size, is 20 microns at the base of the core and 60 to 80 microns at the top (Fig. 3). This increasing trend in grain size is also observed in other sediment cores from shallow reservoir areas and is linked to the ongoing filling of the reservoir and thus to higher river velocity. In this core, grains coarser than 1 mm are mainly plant, shell and anthropogenic debris, such as bottles. Gravel is limited to the central part of the channel of the upper reservoir basin.

In sediment core Lim 18.3, water content of the sediments varies from 39.8 to 52.2%, and is inversely proportional to grain size. Mean water content of all cores is 42%. Volume magnetic susceptibility varies from 5 to 35×10^{-5} . Despite the low signal, local correlation between sandy sequences with higher susceptibilities in different sediment cores is facilitated by this method.

¹³⁷Cs- radioisotope measurements in several cores reveal maximum concentration peaks that are attributed to the Chernobyl accident in 1986 and to the atmospheric bomb tests in 1963-64 (Fig. 3, Dominik et al. 1987).

4. - Sediment contamination

Surface sediments

In surface sediments, hydrocarbon, AOX and PAH values are generally low, but locally the concentrations exceed the legal soil limits. Heavy metal concentrations are compiled in Table 1 and the distribution of surface sediment concentrations are presented in Fig. 4 as enrichment factors compared to natural concentrations in sediments from Lake Geneva (Vernet 1977). These concentrations are: Hg = 0.05 µg/g, Cd = 0.3 µg/g, Cu = 50 µg/g, Pb = 50 µg/g and Zn = 100 µg/g. In general heavy metal concentrations increase towards the lower reservoir basin. Upstream, all concentrations, except for Hg, are within or close to those of the reference case of Lake Geneva.

Sediment cores:

Four different sites have been sampled and sediment core Lim 18 (sub-cores 18.1 to 18.3) has been chosen as a representative example for the history of sediment contamination (Fig. 5).

Sediments recovered from this core span the time from about 1958 to present (Fig. 3). For organic N, total content in P and heavy metals, concentrations are maximum in the

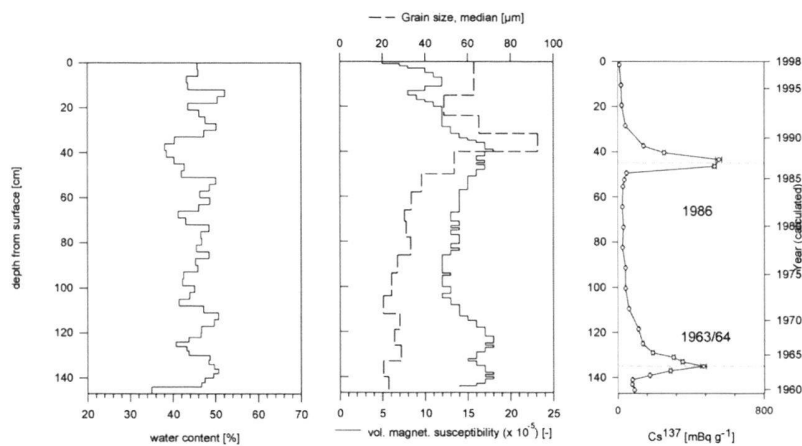


Fig. 3. Sedimentological parameters of sediment core Lim 18 and core dating by Cs137: Water content, grain size, volumetric magnetic susceptibility, Cs-137 dating.

second sample from the base. Concentrations of many elements (Pb, Cr, Ni, Cu, Zn) are about 5 or 6 times higher than those in surface sediments. Enrichment of the elements Cd, Hg, and As, however, is much higher in the lowest part of the core. A rapid decrease in concentration, which varies with the type of element is observed towards the top of the core. An upward decrease in organic carbon concentration by a factor of about two is also observed. PCB and PAH concentrations reach the highest values at the base of the core.

The analysis of all sediment cores shows that metal concentrations are low at the base. High concentrations of metals essentially occur after 1950, reach a maximum shortly after

1960 and then decrease to values similar to those of surface sediments around 1975. As all element concentrations have been measured on sieved sediments < 65 microns, grain size increase on bulk sediment toward the top of the cores does not explain the general trends in concentration profiles.

5.- Interpretation and sediment model

Heavy contamination of sediments during the 1960s and 1970s is linked to high input of untreated or not sufficiently treated waste water to the river. Continuous construction of waste

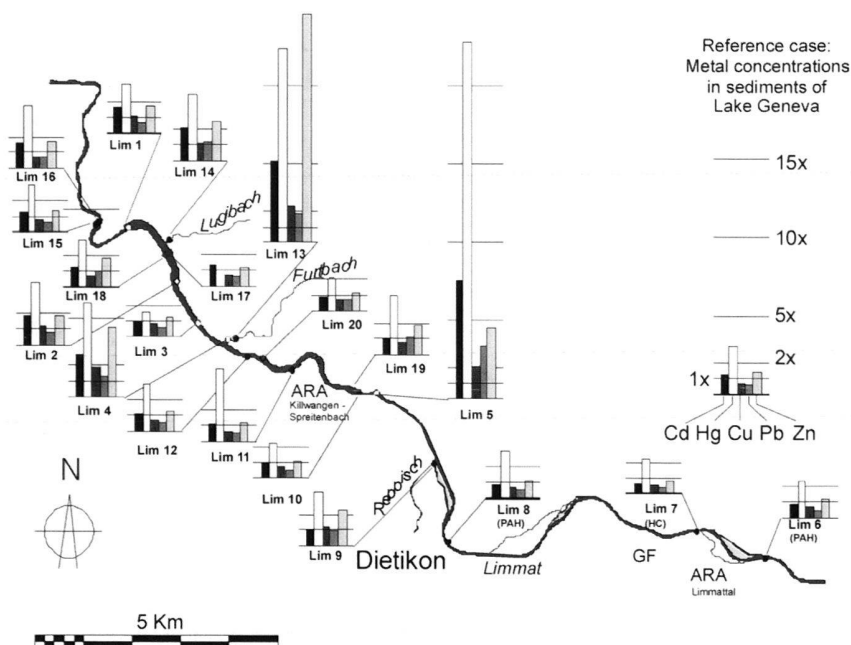


Fig. 4. Surface sediment contamination in the Wettingen reservoir and the river sediments up stream, enrichment factors with respect to natural heavy metal concentration in Lake Geneva (Vernet 1977). HC = Hydrocarbons, PAH = Polychlorinated aromatic hydrocarbons.

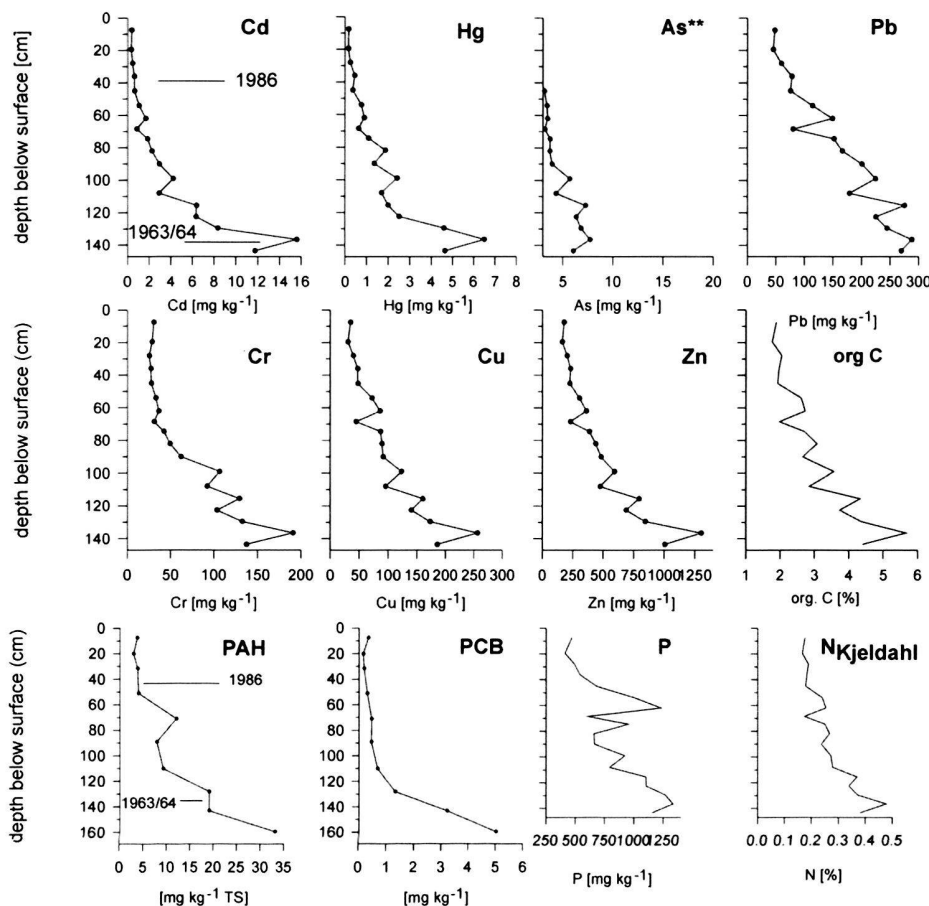


Fig. 5. Sediment contamination in cores Lim 18.1 and 18.3.

water cleaning facilities and their increasing performance, particularly by the introduction of de-phosphatation, in conjunction with new regulations on industrial water, may be responsible of the decrease after 1960.

The explanations for contamination of surface sediments of the reservoir are the following:

- Sample Lim 5: sediments from the years of high concentration in the 1960s and 1970s outcrop on the channel wall.
- Samples Lim 4 and 13: a source of local pollution seems to be responsible for high concentrations in the lowermost riverbed of Furtbach.
- Elevated concentrations in other grab samples are interpreted as the result of reworking as found in sample Lim 5.

Figs. 2 and 6 show the spatial distribution of contamination, based on analytical results from cores and the bathymetric measurements (see chapter 2):

- The lower strata (a) correspond to sediments deposited before 1958, which have moderate contamination.
- Strata (b) represent highly contaminated sediments of the 1960s and 1970s.
- Strata (c) correspond to surface sediments with low contamination.

In the lower reservoir basin, the contaminated strata are generally buried below surface sediments. In the central part of the basin, contamination is either buried or exposed by erosion at the surface. In the upper reservoir, contaminated sediments are either partially eroded, exposed to erosion or remain covered by surface sediments.

1.- Element (all concentrations in µg/g dry sediment)	2.- Swiss limits for soil (VBBo 1998)	3.- Sediments : Natural concentrations in Lake Geneva (Vernet 1977)	4.- Wettingen Reservoir : Surface sediments, mean concentrations of Lim 1-4, 6-12, 14-20	5.- Wettingen Reservoir : Surface sediments Lim 13, (contaminated sediment from local source)	6.- Wettingen Reservoir : Sediment cores, mean concentrations for the year 1986 (low contamination)	7.- Wettingen Reservoir : Sediment cores, mean concentrations for 1963/64 (high contamination)
Extraction method	2M - HNO ₃	(HClO ₄ /HF/HCl)	2M - HNO ₃	2M - HNO ₃	2M - HNO ₃	2M - HNO ₃
As			3.89	5.30	4.05	7.11
B		70.00	39.00	34.00	38.00	36.00
Ca (%)			11.38	10.68	11.33	11.78
Cd	0.80	0.30	0.40	1.57	0.72	12.08
Co		10.00	10.17	9.70	14.10	11.50
Cr	50.00	50.00	34.9	47.20	30.50	162
Cu	40.00	50.00	45.2	118	60.30	219
Fe (%)			2.05	1.97	1.84	1.69
Hg	0.50	0.05	0.17	0.62	0.36	5.08
Mg (%)			1.40	1.57	1.47	1.57
Mn			552	710	385	332
Mo	5.00		0.24	0.56	0.37	0.81
Ni	50.00	50.00	37.66	39.80	39.00	75.0
P			761	1468	887	1258
Pb	50.00	50.00	38.33	90.50	73.34	270
S (%)			2.9	4.60	3.25	6.12
Sb			<0.13	<0.13	<0.13	<0.13
Sn		8-10	0.21	0.88	0.19	4.66
V		50.00	24.0	19.90	18.22	18.90
Zn	150	100	175	1460	210	1037
Hydrocarbons (bulk)			66.4	142	110	305
AOX (Cl, µg/g dry sediment)			29.2	34	31	305

Table 1: Compilation of sediment contamination in the Wettingen Reservoir (sampling positions see Fig. 1).

6. – Discussion and conclusion

Periodic depth measurements along fixed sections since construction of the dam and new 3D mapping by modern sonar techniques and DGPS localisation provide data for a geometric model and the sedimentary history of the Wettingen reservoir from 1933 to the present. The combination with geochemical

analysis reveals the presence of a large volume of contaminated soft sediments, which have been mainly deposited during the 1960s and early 1970s. These sediments are underlain and overlain by less contaminated deposits (Fig. 2 and 6).

The presence of contaminated reservoir sediments naturally raises the question of risk to human health and the environment and of future reservoir use and management.

According to Swiss legislation, contaminated off-

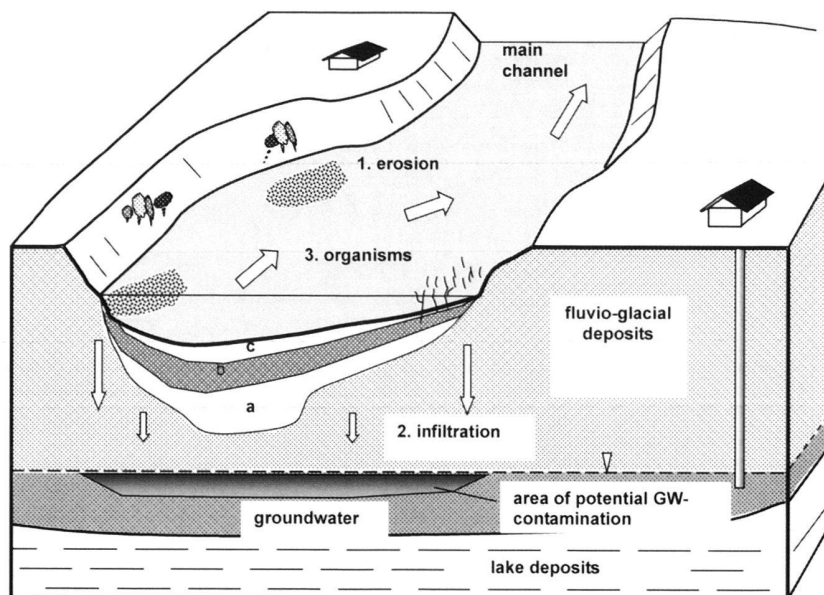


Fig. 6. 3D-model of the reservoir basin fill and risk analysis

shore sediments are only mentioned in BUWAL (1995), which addresses the dredging of harbour sediments. Legislation on contamination of soil could, however, also be applied as a legal base for evaluating the risks mentioned above. Regarding the short list of contaminants stated in the ordinance on soil protection (VBBo 1998), all heavy metal and organic compound concentrations in the contaminated reservoir sediments exceed the "limit of investigation". In this case possible impact on human health, on animals and plants needs to be investigated by the proper authorities.

For the reservoir sediments, the following potential risks have been identified (Fig. 6):

- Uptake of contaminants by aquatic organisms (sediment breeders) and plants.
- Erosion and re-suspension of contaminated sediments in the surface water.
- Groundwater contamination, either by surface water, with high content in dissolved organic carbon, after erosion of fine reservoir sediments, or by infiltration of surface water through contaminated reservoir sediments.

Recently, a research and monitoring program targeting these risk factors has been defined and activated.

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Abreviations:

AOX = Adsorbable halogenated hydrocarbons
 PAH = Polychlorinated aromatic hydrocarbons
 PCB = Polychlorinated Biphenyls

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