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SEDIMENTATION PROBLEMS IN THE RESERVOIRS OF THE KRAFTWERKE SARGANSERLAND - VENTING OF TURBIDITY CURRENTS AS THE ESSENTIAL PART OF THE SOLUTION [*]

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1. INTRODUCTION

The hydroelectric power scheme “Kraftwerke Sarganserland” (KSL) was completed in 1978. The power plants are situated in eastern Switzerland, southwest of Bad Ragaz in the valley of the Tamina, an affluent of the Rhine River. The two power plants in Mapragg and Sarelli use the water from a 159 km^2 catchment area and have a maximum installed capacity of 370 MW. The annual power production averages 443 GWh of mostly peak power. The water is stored in the two reservoirs Gigerwald and Mapragg.

Bathymetric measurements made during the last few years have shown that the level of sedimentation is particularly close to the bottom outlet and has become a problem. In Mapragg the sediments have risen above the base level of the bottom outlet. To guarantee the safe operation of the dams the bottom outlets have to be able to be opened at any time. Therefore solutions have to be

[*] *Problèmes de sédimentation dans les réservoirs des Kraftwerke Sarganserland, Passage des courants de turbidité par la vidange de fond comme clé de la solution.*

found. It is assumed that the sedimentation problems will get worse due to global warming, which results in more intense rainfall, the melting of the perm frost and the decline of the glaciers [1].

The first attempt at removing the sedimentation was carried out at the Mapragg site in the summer of 2005. It consisted of excavating the material using air lift technique and adding it to the water flowing through the penstocks. From there the sediments were released to the Rhine River in Bad Ragaz. A second attempt was made in 2006 but the results were not very good. The situation was made worse because during that time period huge volumes of sediments were deposited in the reservoirs due to major flood events, and also because the excavation of the sediments at the upper reservoir, Gigerwald, was judged to be very difficult. Looking for a solution, the KSL gave to the technical support team of the Nordostschweizerische Kraftwerke AG (NOK) the mandate to carry out an extensive sedimentation study. The aim of the study was to find economically and ecologically feasible measures that could be taken to prevent sedimentation. Part of this study has been performed within the frame of an MAS thesis work at the EPFL-LCH [2]. The first results of this study are described in the following. As part of the solution a concept for venting of turbidity currents was developed.

2. OVERVIEW OF THE KRAFTWERKE SARGANSERLAND

Fig. 1 shows an overview of the hydropower scheme of the Kraftwerke Sarganserland KSL. The location of the installed turbidity measurement sensors can also be seen on the map.

The reservoir Gigerwald stores 33.4×10^6 m^3 of water from a catchment area of 52 km^2 in the Calfeisental valley and 45 km^2 in the Weisstannental valley. Water from the Weisstannental is diverted into the Gigerwald reservoir by way of an adduction tunnel. A pressure tunnel connects Gigerwald with the power house and the compensation reservoir at Mapragg (Volume of 5.3×10^6 m^3). The catchment area of Mapragg is 62 km^2. When the power prices are low, water is pumped from Mapragg (865 m a.s.l.) to Gigerwald (1'335 m a.s.l.). The water leaves this closed system through a pressure tunnel between Mapragg and the power house at Sarelli in the Rhine Valley.

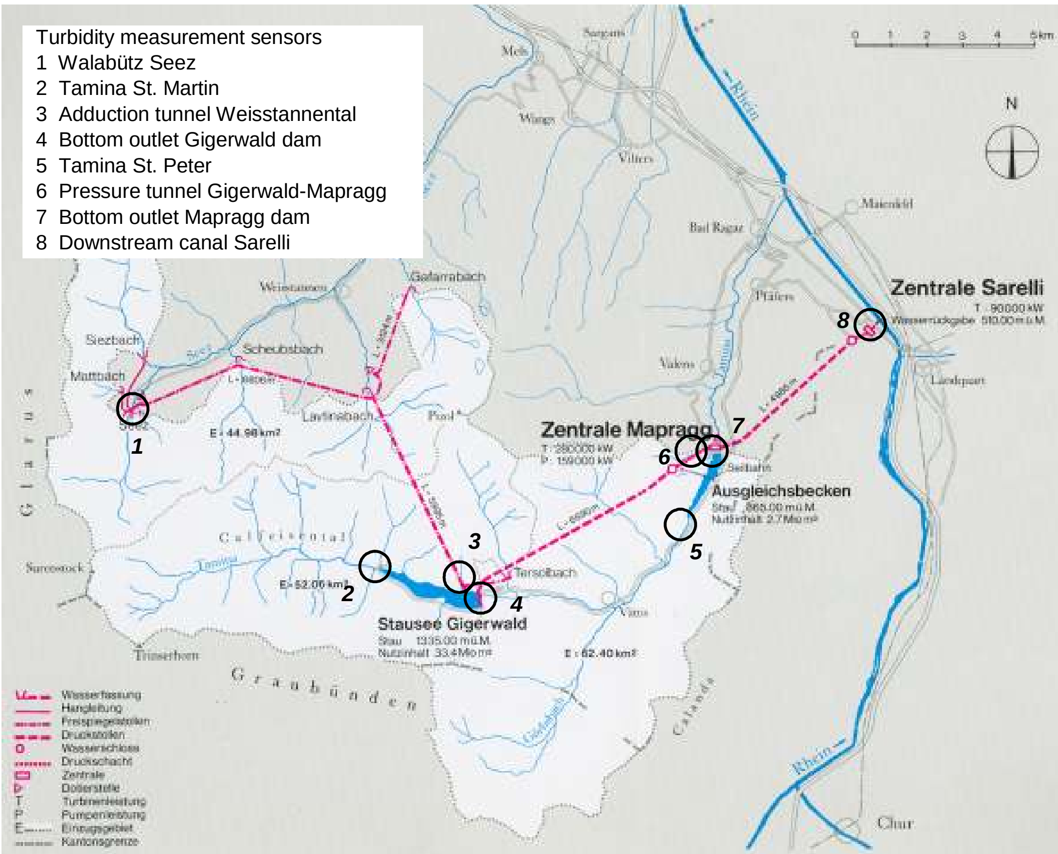

Fig. 1

Layout of the hydropower scheme of the Kraftwerke Sarganserland KSL and locations of the turbidity measurements

Schéma de l'aménagement hydroélectrique des Kraftwerke Sarganserland KSL et emplacements des stations de mesure de turbidité

3. ANALYSIS OF BATHYMETRIC MEASUREMENTS AND ANNUAL RATE OF SEDIMENTATION

3.1. MAPRAGG RESERVOIR

Bathymetric measurements using GPS and sonar were performed every spring and autumn since September 2003. The data was then compared with the original terrain data from the reservoir and the result is the sedimentation volume (see Fig. 2).

The total sedimentation volume in December 2007 was around 560’000 m^3, which corresponds to an average volume loss per year of 18’000 m^3 or 0.4 % of the total storage volume. The data also shows that consolidation of the sediments occurs during the winter months as the volume decreases slightly.

The data from October 2004 appears to be incorrect, and the sedimentation volume between April and December 2006 increased by 46'000 m^3. The sediment level close to the dam is already 3 m higher than the base level of the bottom outlet opening. The material causing the sedimentation close to the bottom outlets is mostly silt and only in very small volumes sand and gravel.

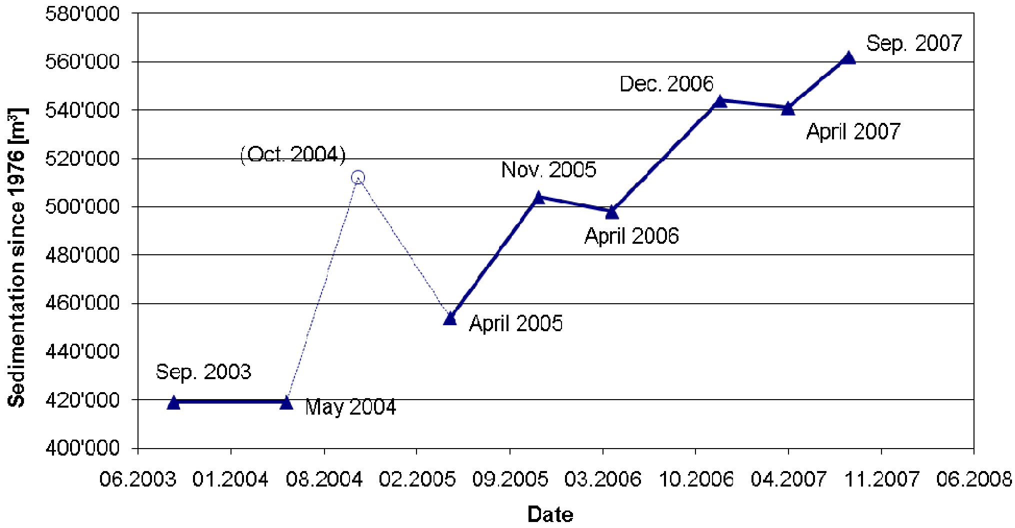

Fig. 2

Sedimentation volume in the Mapragg Reservoir since 2003 (the data from October 2004 is probably inaccurate and the data points have been adjusted to account for extracted sediment volumes)

Volume de sédimentation dans le réservoir de Mapragg depuis 2003 (les données d'Octobre 2004 sont vraisemblablement erronées, et les volumes ont été corrigé tenant compte de l'extraction de sédiments)

3.2. GIGERWALD RESERVOIR

The bathymetric survey at the Gigerwald Reservoir shows that sedimentation is also a problem. The total sedimentation volume is estimated to be 1.7 x 10^6 m^3, which is equal to 5 % of the total storage volume. The loss of volume averages 60'000 m^3 or 0.2 % per year. During the summer of 2006 an increase of 90'000 m^3 was measured. The sedimentation level at the dam has increased an average of 0.75 m per year since 2003 and is now only 5.4 m below the intake of the bottom outlet and the pressure tunnel (one common intake structure). It is assumed the level of the sediment will reach the intake structure in 5 to 15 years.

4. ANALYSIS OF THE TURBIDITY MEASUREMENT DATA

In the spring of 2005 a number of turbidity measurement sensors were installed in order to measure where and when the solids flow into the reservoirs. Measurements were taken at the major natural inflows, the adduction tunnel transporting water to the Gigerwald reservoir, the pressure tunnel between Gigerwald and Mapragg, the free surface canal downstream of Sarelli and in the Mapragg and Gigerwald reservoir at the level of the bottom outlets. The solid concentration was measured every 2 to 4 minutes. Due to technical problems the data from the sensor at the bottom outlet Gigerwald could not be used.

4.1. SOLID CONCENTRATION MEASUREMENTS

The results of the measurements can be summarized as follows:

- The maximum solid concentrations of up to 35 g/l were measured in the natural inflows as well as in the adduction tunnel. At normal discharge the concentrations were in the range of 0.05 to 0.30 g/l.
- Several turbidity currents were measured in Mapragg. Water with high solid concentration levels enters the reservoirs and the sediment settles due to its higher density. If the concentration of the incoming water is high enough and the slope of the reservoir is steep enough, a turbidity current is formed and flows along the talweg, which is physically comparable to a powder snow avalanche [3] (see Fig. 3). Measurements at Mapragg confirmed that if the current is strong enough, the sediments can reach the dam. Several times and within a very short period of time the solid concentration at the bottom outlet rose up to maximal 14 g/l (see Fig. 4 for the floods of September 17th and 18th 2006). The bottom outlet had to be opened and flushed after these the two major flood events for safety reasons as the valve to divert water into the Tamina was blocked.
- The 13 rain events in 2005 and 2006, which caused an increase in the solid concentration levels at the bottom outlet Mapragg, were studied explicitly. The five most extreme events with maximum solid concentrations above 5 g/l at the bottom outlet can be characterized as follows: the solid concentration at the inflow was above 5 g/l for at least 8 hours and the peak concentration was at least 16 g/l. Events with lower solid concentrations or of shorter duration caused weak or no turbidity currents.
- Solids carried to the dam by the turbidity currents settled within hours, but also settlement times of as long as 1-2 days were observed.

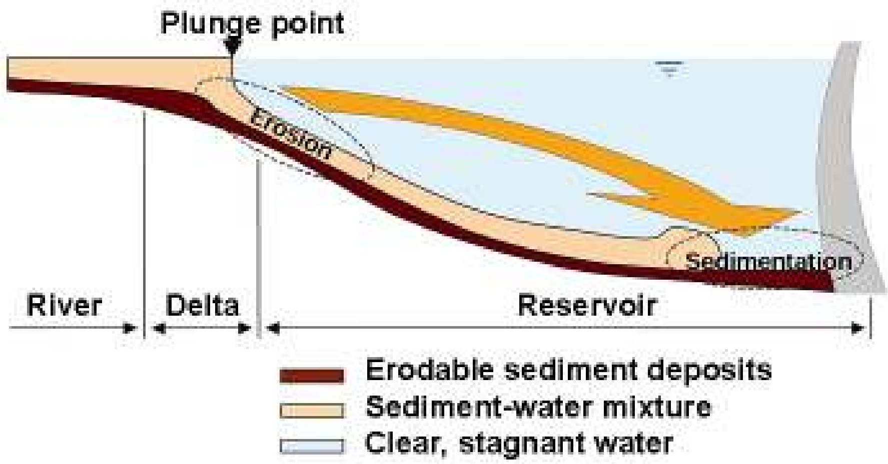

Fig. 3
Schematic drawing of sediment transport within a reservoir due to turbidity currents [4]
Schéma du transport solide dans un réservoir par courant de turbidité

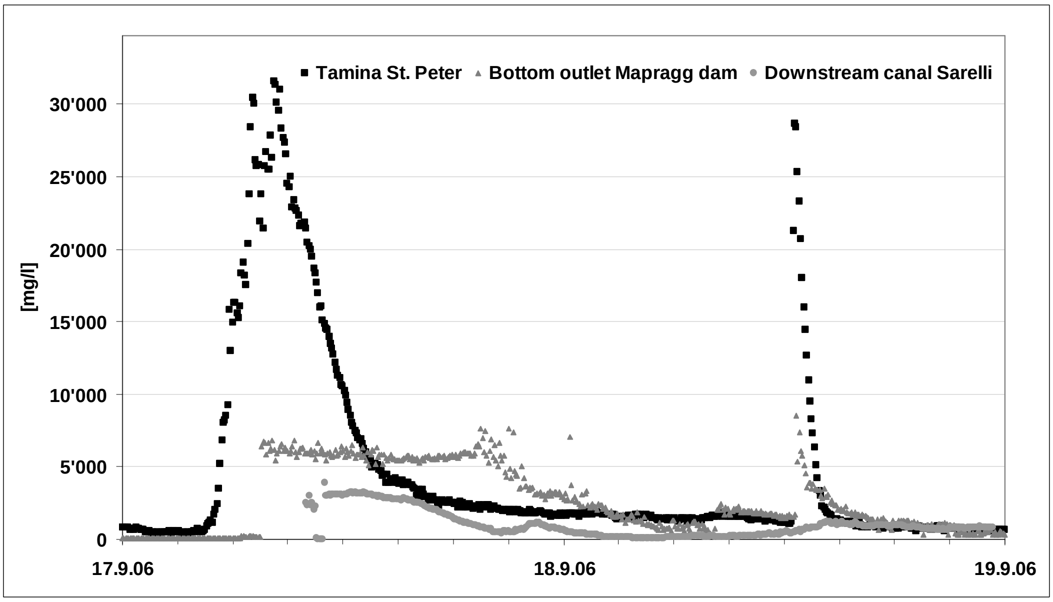

Fig. 4
Solid concentration in Mapragg during flood events on September 17th and 18th 2006
Concentration de matière en suspension pendant les crues du 17 et 18 septembre 2008

4.2. SOLID LOADS CARRIED TO THE RESERVOIRS

Using the solid concentration and water discharge data the solid loads were calculated. The sum curve for the Mapragg reservoir for 2006 can be seen in Fig. 5. The results for the solid loads can be summarized as follows:

- The major solid inflows take place during a few rain events generally between June and September. 60 to 70 % of all solid inflows in Mapragg occurred during the above-listed rain events when the concentration levels at the bottom outlet rose above 2 g/l due to a turbidity current.
- In Mapragg 70 % of the sediment comes from the natural catchment area and 30 % through the pressure tunnel from Gigerwald. Of the total amount of 58'000 t during the summer of 2006 14 % of the solids were pumped back to Gigerwald and 26 % left the system by way of the pressure tunnel to Sarelli. 35'000 t of solids remained in the reservoir.
- Due to incorrect measurement data for Gigerwald, a balance of the solid inflow cannot be calculated. An estimation using the valid values shows that 40 to 50 % of all solid inflows into Gigerwald comes from the Weisstannental and flows through the adduction tunnel. The rest of the solids comes from the natural catchment area. The deposits in Gigerwald during 2006 are estimated to be 70'000 t.

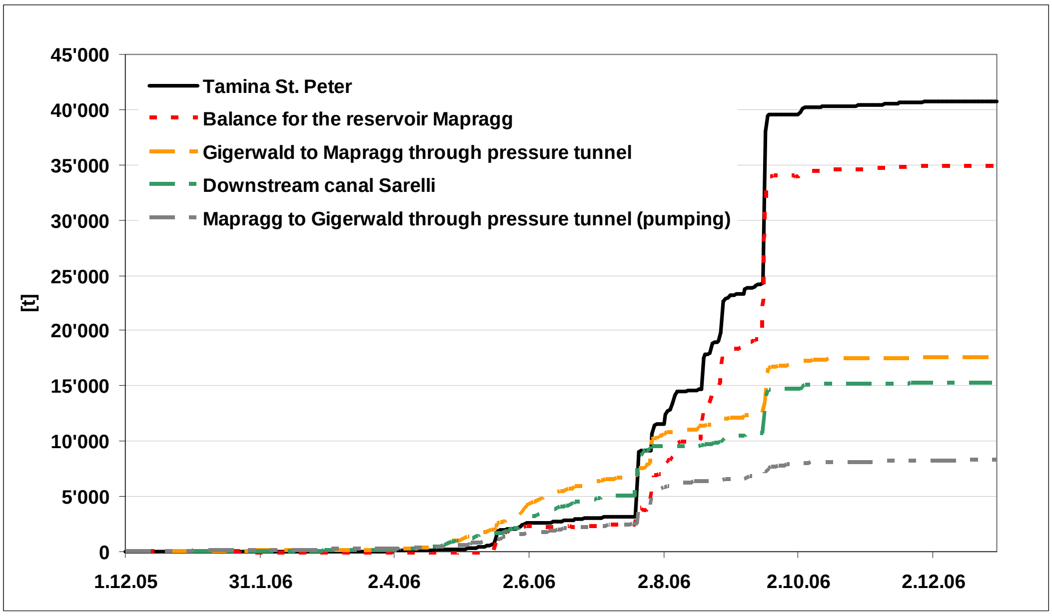

Fig. 5
Sum curve of solid input and output of Mapragg
Cumul des apports et des sorties de sédiments à Mapragg

5. IDENTIFICATION OF FEASIBLE MEASURES TO PREVENT SEDIMENTATION

Fig. 6 shows possible measures which could be taken to reduce sedimentation. They can be classified as measures within the catchment area, in the reservoir or at the dam [5]. For the power plants at Sarganserland the focus was set to find a sustainable solution, which prevents the sedimentation volumes in both reservoirs from increasing any further. The listed measures are already categorized into priority and secondary measures as well as into non sustainable or non feasible measures.

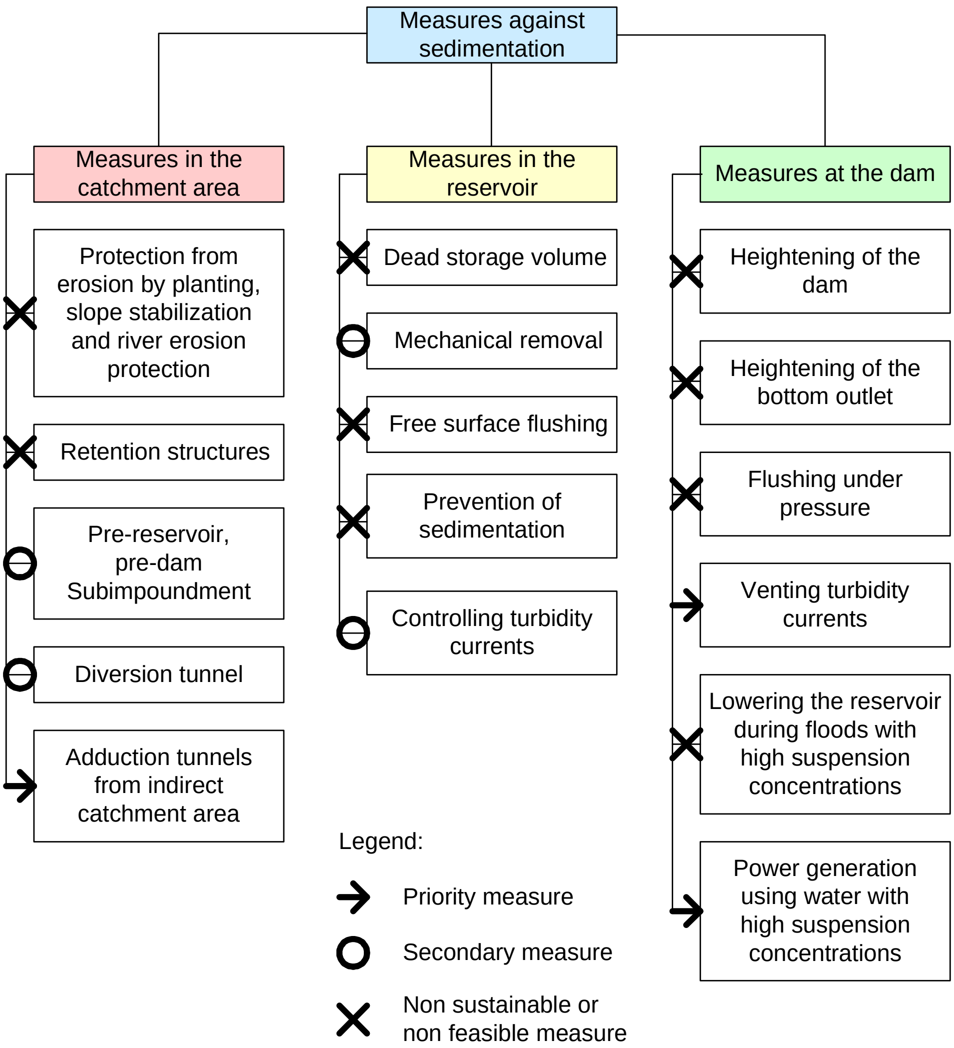

Fig. 6
Overview of possible measures to prevent sedimentation categorized into priority, secondary and non sustainable or non feasible measures for KSL
Vue d'ensemble des mesures possibles pour la prévention de la sédimentation classées par priorité, mesures complémentaires et non réalisables dans cadre de KSL

As a result from the studies the following three priority measures were recommended:

1. *Adduction tunnels from indirect catchment area:* A measure to prevent sedimentation is the automatic closing of the water intakes in the Weisstannental during flood events. 40 to 50 % of all solids being brought to Gigerwald come from the Weisstannental and mostly during a few rain events in summer. The reduction of sediment by not diverting water with high suspension concentration levels would be a big step towards minimizing the inflow of sediment. From the economical point of view the loss of water is smaller than the gain for not taking in the sediments. This automation has been installed in spring 2008, so that water having a higher solid concentration than 4 g/l is not being taken any longer.

2. *Venting turbidity currents at Mapragg:* A promising measure is the venting of the turbidity currents. The turbidity measurements have shown that large sediment inflows were transported to the dam by turbidity currents during a few flood events in summer. If the bottom outlet could be opened to discharge water with high suspension concentrations during these events, relevant loads of sediments would leave the reservoir. This expectation is based on the experience gained from a large flood event in August 2005. The bottom outlet at Mapragg was opened, because the reservoir was completely full. The opening of the bottom outlet caused incoming turbidity currents to be vented. The solid output through the bottom outlet was calculated to be 6’000 t. The loss of water has to be considered when considering the economics of discharging suspension through the dam. If venting in Mapragg starts at a suspension concentration of 2 g/l the loss of revenue is equal to the cost of the mechanical excavation done by air lift, which would be necessary if the sediments remain in the reservoir. Measurements taken in the past have shown that concentrations up to 14 g/l can be expected. A concept for venting turbidity currents in Mapragg is described in the next chapter. The permission from the authorities to do so was given in Summer 2007. Since then venting of turbidity currents is performed when the concentration level at the bottom outlet raises above 2 g/l.

3. *Power generation using water with high solid concentration:* A further promising measure is to run the turbines when solid concentrations are high either in Gigerwald or in Mapragg. Damage to the turbines due to abrasion is not expected judging from past experience gained during the excavation with the air lift. Efficiency can become bigger if a suction head is installed before the inlet structure of the pressure tunnel, so that water from deeper layers with higher solid

concentrations is taken in. For Gigerwald starting the turbines at high solid concentration will transport the sediments down to the lower reservoir Mapragg. Here a solution will have to be found to prevent the sediments, flowing out of the pressure tunnel at the dam, from settling in the reservoir and instead are either vented through the bottom outlet or leave the reservoir via the pressure tunnel to Sarelli. A possibility to do so is to hang a geotextile curtain 50 m upstream of the dam across the reservoir to help keep the sediments close to the dam and the outlet structures. The effect of such a geotextile curtain will have to be first investigated using a 3D numerical model.

From today's point of view it is sure that these three "priority measures" will only reduce but not stop the sedimentation problem of the Kraftwerke Sarganserland. The monitoring of the next years will show, how and if "secondary measures" are to be implemented. Then mechanical removal has to be considered again. The construction of a pre-reservoir including mechanical removal in the pre-reservoir or excavation in the reservoir itself is technically possible but expensive. Depending on the solution in Gigerwald a diversion tunnel in Mapragg could be feasible too, if sediments from Gigerwald are flushed or vented down to Mapragg. A pre-dam could also stop a turbidity current from flowing down to the bottom outlet. The other listed measures in Fig. 6 to prevent sedimentation are neither feasible nor economical nor sustainable.

6. CONCEPT FOR VENTING TURBIDITY CURRENTS AT MAPRAGG

When high suspension concentrated water enters into the reservoir of Mapragg for longer than one hour and with higher concentration then 10 g/l, the turbidity sensor in St. Peter is activated and a first alarm is being sent. The time and concentration limits to activate the alarm are based on the results from the measurements done in the past years. The probability is expected above 60 % that a turbidity current is formed and flowing down to the dam and a solid concentration level higher than 2 g/l at the bottom outlet is measured. If so, a second alarm is sent out. After this second alarm the opening of the bottom outlet has to occur rapidly.

Depending on the measured solid concentration at the bottom outlet, the maximum discharge is limited between 5 and 25 m^3/s. Fig. 7 shows the discharge for a measured solid concentration above 11 g/l.

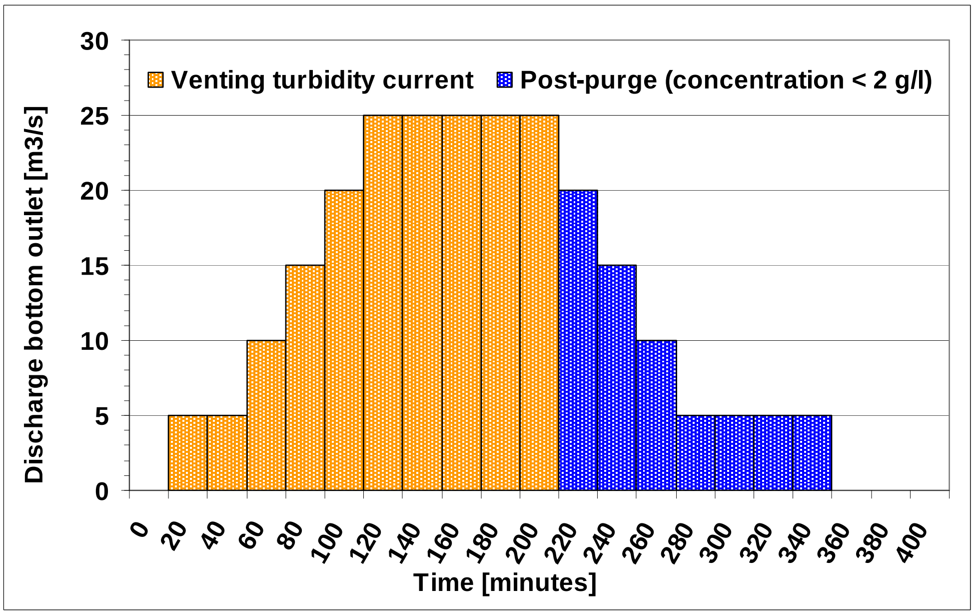

Fig. 7
Discharge during and after venting of a turbidity current for a concentration above 11 g/l
Débit pendant et après avoir purge un courant de turbidité d'une concentration de 11 g/l

The increase and the decrease of the discharge are comparable with natural floods or other artificial floods in Switzerland. Since the discharge capacity of the Tamina River in Bad Ragaz is limited to 30 m^3/s, the discharges of the affluents underneath Mapragg have to be considered when opening the bottom outlet. After the concentration falls below 2 g/l, a post-purge is operated and the bottom outlet is closed again.

From an environmental point of view no negative effects are expected, since the solid concentrations discharged are lower than what they would be during a natural flood event. The artificial floods might even have a positive effect due to the dynamic effects on the river.

During a period of five years the efficiency of venting of turbidity currents and its effects on the environment will be tested and monitored.

7. CONCLUSIONS AND OUTLOOK

To ensure that the sedimentation problem in the reservoirs of the “Kraftwerke Sarganserland” does not increase, measures against sedimentation had to be implemented rapidly. As an immediate measure for Mapragg, the operational sequences for venting turbidity currents were set. For Gigerwald the automation of the water intakes in the “Weisstannental” was installed, so that during flood events water with high suspension concentration levels will no longer be diverted. The possibility of starting the turbines at high solid concentration to evacuate sediments has to be analyzed in details first, since coordination with the power market complicates the situation. The monitoring of theses measures during the next years will show the efficiency. Then further measures against sedimentation as described above are to be implemented if necessary.

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SUMMARY

The volume of sediment accumulating in the two reservoirs of Kraftwerke Sarganserland (Forces Motrices Sarganserland) is increasing at an annual rate of 75,000 m^3, which corresponds to a volume loss of 0.2 % per year in the Gigerwald reservoir and 0.4 % in the Mapragg reservoir. The main problem is sedimentation near the dam upstream of the bottom outlets. At Mapragg, the sediment is currently reaching a level above the base level of the bottom outlets. Thanks to concentration measurements in the affluents, it is possible to show that most solids flow in during summer flooding events. At Mapragg, several turbidity currents were observed that transported suspended solids to the dam toe. Several measures to solve the sedimentation problem were considered and compared. For Mapragg, an emergency measure was recommended, which is to vent turbidity currents through the bottom outlets. A technical feasibility concept was developed and implemented. For Gigerwald, the automation of the intakes in the lateral valley of Weisstannental was set up as a priority measure to limit the inflow of solids during flood events.

RÉSUMÉ

Le volume des sédiments accumulé dans les deux réservoirs des Kraftwerke Sarganserland (Forces Motrices Sarganserland) augmente annuellement de 75'000 m^3, ce qui correspond à une perte de volume de 0.2 % par année au réservoir de Gigerwald et de 0.4 % au réservoir de Mapragg. Le problème principal est le niveau des sédiments près du barrage en amont des vidanges de fond. A Mapragg, les sédiments atteignent déjà aujourd'hui un niveau supérieur à la cote du radier de la vidange de fond. Grâce aux mesures de concentration dans les affluents, il est possible de montrer, que la plupart des apports solides arrivent lors de quelques événements de crue pendant l'été. A Mapragg plusieurs courants de turbidité ont été observés qui apportaient des matériaux en suspension jusqu'au pied du barrage. Plusieurs mesures pour résoudre le problème de la sédimentation ont été envisagées et comparées. Pour Mapragg, il est recommandé, comme mesure d'urgence, de faire transiter les courants de turbidité par la vidange de fond, un concept de faisabilité technique a été développé et implémenté. Pour Gigerwald, l'automatisation des prises d'eau dans la vallée latérale “Weisstannental“ a été réaliser en priorité pour limiter les apports solides en cas des crues.