Alternative hydropower development for large rivers – the ecologic and economic “TUM multi-shaft” concept

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1. Introduction

The future potential for hydropower is still very large especially in non-OECD countries where a growth factor of about three is expected until 2035. However, many of the future hydropower potentials coincide with so called mega-fauna hotspots. It will be therefore vital to think of where hydropower will be built and what concepts will be used in the future. Hydropower at sensitive sites should consider, not to change the flow depth and flow velocities of the rivers too much. Thus suspended and bed-load transport will not change and habitat conditions for aquatic species are preserved. Additionally, hydropower must offer fish a high level of protection against damage in the turbine and a suitable upstream and downstream migration path.

In 2009 the so called TUM hydro shaft concept has been invented at the chair of Hydraulic and Water Resources Engineering of Technische Universität München (TUM), Germany. The patented concept is well suited to use the energy of natural and artificial river steps and consists of a shaft which sits in the river bed, a horizontal trash rack with cleaner, a subsurface turbine with permanent magnetic generator followed by a suction pipe to release the water into the downstream. Later a second patent has been applied for, the so called TUM multi-shaft concept, which uses several shafts and combines them with integrated eco-migration corridors in the axis and on both sides of a river.

Tests have been conducted with a small pilot of the TUM hydro shaft and with almost 2000 fish of five differing species and lengths varying from 50mm to 200mm. Especially the probability for downstream migration and the probability of fish damage in the turbine have been investigated. As a summary of all the tests one can say that about 2/3 of the fish migrated into the downstream over the provided bypass. The probability of taking the passage through the turbine was higher for small fish, contrarily the probability of damage during turbine passage was higher for larger fish. As a summary in the very small turbine (750mm diameter, 333 rpm) almost 7% of the fish were killed. For prototype plants with larger turbines and lower rotational speeds mortalities well below 2% can be expected.

Considering the high level of fish protection, the minimum changes to suspended and bedload transport a preliminary design of the multi-shaft concept for the Mekong River has been worked out in a master thesis by N. Grönitz. Instead of one large power plant three smaller multi-shaft plants with a head of less than 10m each were suggested. Thus, beside the fish protection aspects, the inundated area can be reduced, the change in flow depth is limited and free flowing sections are provided in between two hydropower plants. From an ecologic point of view such a concept is certainly superior but also the economy of the solution does not clearly speak against it. Certainly not, if ecological disadvantages, reduction of fish populations or additional costs for erosion protection measures in the downstream section are considered.

2. The TUM hydro shaft and multi-shaft hydropower plant concept

The TUM hydro shaft (TUM-HSPP) concept is a completely new, innovative and fish-friendly HPP concept. The concept has already obtained a German and an U.S. patent. Other patents are currently pending. So far seven patent families exist. The idea of the concept is to put a concrete box into the river with a trash rack which is horizontal to the river bed. This setup has a few hydraulics, sediment related and eto-hydraulic advantages that will be explained in the next section in more detail. Furthermore, the simple geometry of the construction is very easy to plan and design, can be scaled from small to large and can be produced in a cost-efficient pre-fabrication process.

2.1 The TUM hydro shaft concept

The TUM-HSPP consists basically of a very simple and rectangular concrete box, a trash rack with underwater cleaner and a downstream gate placed in the breach of the original concrete weir (see Fig. 1). Usually the modifications to the existing concrete works are small and the new shaft can be prefabricated and set in place in very short time. Besides these advantages it was the idea behind the concept to develop not only a costly but also an efficient and ecologic concept.

In a classical concept the cost drivers are the individual and complicated design of each plant, the complex and expensive formworks, the long construction time and the large infrastructure needed to build the plant. From experiences so far, and one has to admit that all situations are somehow unique and costs must be seen in the context of each site, we currently computed a cost reduction with the present concept by some 30% compared with classical designs. This is due to the extremely reduced concrete volume mainly, whereas the steel works and building in the river make the concept more expensive than classical bay type HPPs

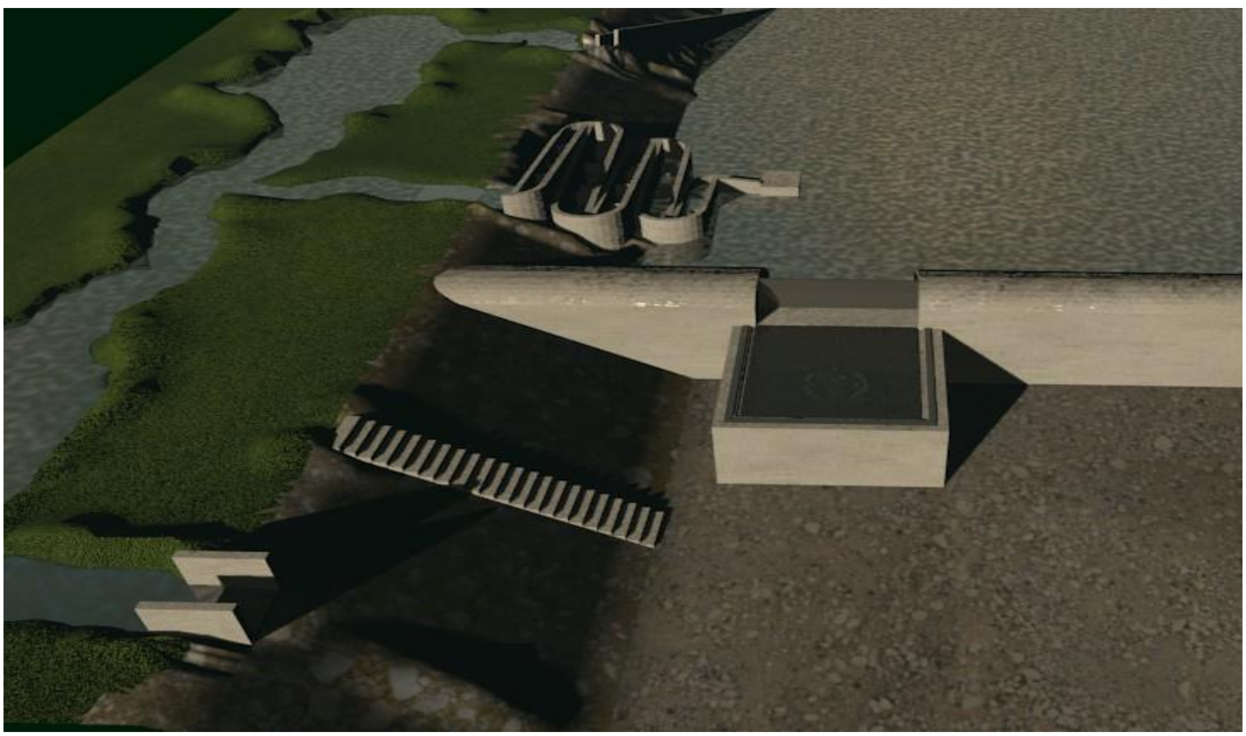

Figure 1: Computer visualization of a classical TUM-HSPP originally intended for energy production at existing weirs (courtesy J. Frank).

Costs are of course important but on the other hand it was also the idea of the inventors to create hydraulic and ecologic advantages with the new design. Among these the following points were considered: High efficiency, reduction of fish mortality at the plant, excellent upstream and downstream passage of fish and other aquatic species, sediment and suspended transport through the plant, aesthetic and invisible design and no detectable noise or vibrations. For many of these topics costs are the decisive factor and corresponding measures are therefore often disregarded. The TUM-HSPP has a few advantages with respect to these points:

- In order to protect fish from being sucked into the turbine a low and uniform velocity distribution and therefore a large intake cross-section is helpful. Whereas in a conventional plant a large cross-section in an almost vertical plane requires digging into depth or width, which is always expensive, the horizontal plane can be increased relatively simple and cost-effective by increasing the box and therefore the length and width of the intake section. The cross-section is usually designed in a way to achieve average velocities of about 0,3m/s.

- Fish can be mechanically protected by a narrowly spaced trash rack. Such a trash rack usually means high head losses and therefore high production losses. With the low velocities at the shaft power plant intake, these losses are hardly measurable and the same applies to the non-streamlined shape of the box.
- In order to enhance safe downstream migration of fish the fish should very easily find the migration bypass. When fish are following the main flow to the turbine this means that the downstream migration path should start in the vicinity of the intake section. In the TUM-HSPP concept a bottom near or surface near opening in the downstream gate enables this in an efficient and easy way (see also Fig. 3).
- Sediment and suspended material is usually trapped upstream of a hydropower plant. For the TUM-HSPP the height of the trash rack plane limits sedimentation. All sediments above the trash rack plane will sooner or later be flushed over the weir when the downstream gate is opened or sucked into the turbine if the grain size diameter is small enough.
- With a permanent magnetic and therefore submerged generator the hydropower plant is not visible and not acoustically detectable. Therefore, the TUM-HSPP can even be used in monument conservation environments.
- The trash rack cleaning with a completely submerged cleaner is tricky because the cleaner represents the most error-prone element of the plant. After many field tests a reliable design could be developed.

2.2 The TUM multi-shaft concept

As mentioned before the TUM-HSPP concept was invented to gain additional energy production at existing concrete weirs. Later a variant of the design has been developed which is suitable for constructing a plant in a natural and constructionally not affected larger river. The design is called the TUM multi-shaft hydropower plant (TUM-MSHPP) concept and is illustrated in Fig. 2. The design is characterized by bays in which one or several shafts may sit, and by so-called eco-migration corridors in the river axis and at each of the river banks. The ideal position of theses migration corridors make findability and therefore upstream migration for fish easy. Whereas conventional river hydropower plants usually consist of a weir block and a power-house block the TUM-MSHPP fulfils both functions through the shaft modules alone, allowing with the downstream gates an impoundment of the upstream reservoir. During floods the cross section can be completely given free by lowering the gates.

Figure 2: Visualization of the TUM-MSHPP. Eco-migration corridors mainly for upstream migration are positioned in the axis and at the river banks (courtesy J. Frank).

3. The 35kW pilot plant test site

3.1 Test installation

In order to investigate the hydraulics, sediment issues and behaviour of fish and in order to technically develop the concept a 35kW pilot plant was built at the Oskar von Miller Institute, the hydraulic laboratory of TUM in Obernach, Bavaria. The TUM-HSPP concept was equipped with a conventional Kaplan turbine, having only a permanent magnetic generator as a peculiarity. Besides, the plant was equipped with a specifically developed trash rack bar profile and a newly developed underwater trash rack cleaner of Muhr company, Brannenburg, Germany. The pilot plant used water from the Isar River diverted over a weir into the Lab and measured in a measuring flume with a calibrated Thomson wear (see Fig. 3). Very precise discharge measurements with the Thomson-weir allowed to determine the maximum efficiency of the plant, defined as the ratio of measured output at the clamps to theoretical hydraulic potential, to 87%.

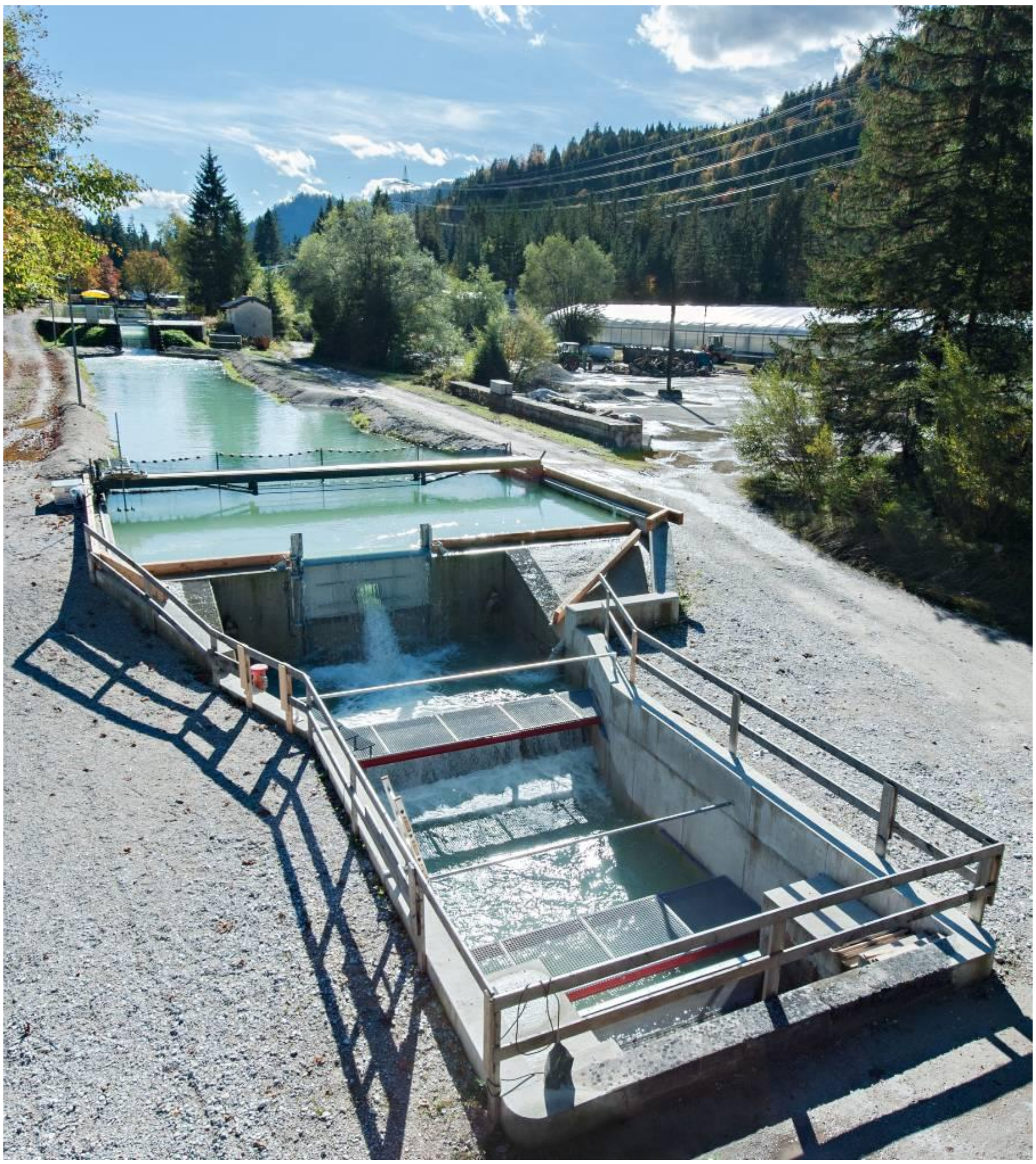

Figure 3: 35kW pilot plant at the Oskar von Miller Institute in Obernach, Germany.

In order to perform etho-hydraulic tests about behaviour and damage of fish at the hydropower intake and during downstream migration the test site was equipped with an upstream, and two downstream basins separated by perforated steel sheets in order to avoid fish to leave the test site. The setup is illustrated in Fig. 4. Test with fish followed the following pattern: The fish, usually captured in wild rivers, were brought to the Lab at least 48h in advance in order to adapt to the local water temperature, then they were released for the tests into the upper basin (coloured in blue), and the test run then over a period of 24h. Fish that migrated downstream had two options to follow: One over the provided bypass the other through the turbine. Fish that migrated over the bypass ended up in the downstream basin following the gate (green color), fish that migrated through the turbine ended up in the basin downstream of the suction pipe (orange colour). Hourly during the test and at the end of it the fish were taken off the water with a catcher from all basins and then they were counted. Fish that migrated through the turbine and survived were under observation for another 96h in order to consider secondary or inner damage.

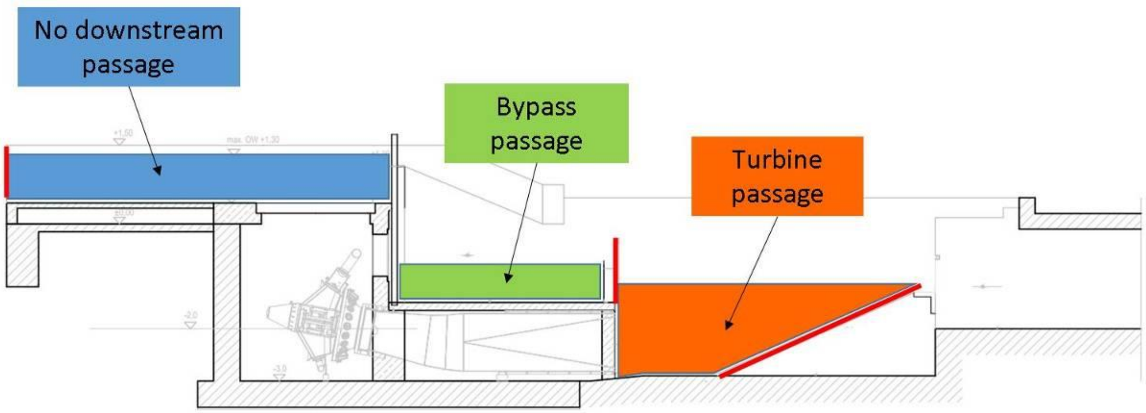

Figure 4: Longitudinal Section through the pilot plant site. The fish were released in the upstream basin (blue) and collected in the catchment ponds after bypass use (green) or after turbine passage (orange), Geiger et al. 2015.

3.2 Etho-hydraulic tests with fish

Ethohydraulic tests were conducted with five different species of fish of different sizes. The following fish species and fish numbers were inserted into the upstream basin:

Fish species	Number of fish	Averaged body length [cm]	Standard deviation [cm]
Brown trout	787	14.4	4.5
Grayling	733	14.3	4.4
Barbel	63	9.9	5.1
Minnow	44	5.9	0.8
Bullhead	252	8.1	1.4

Table 1: Tested fish species, numbers of individuals and average lengths.

The tests showed that the fish in general tried to avoid entrance through the trash rack into the turbine due to the unfamiliar flow situation. Therefore the horizontal trash rack very much acted as a behavioral barrier. Underwater cameras allowed to observe that fish had no difficulty to swim over the intak at the trash rack for several hours. No fish was pressed to the trash rack and could not freely swim as desired. Certainly the low velocities in the intake section were the reason for this. Also it could be observed that about 2/3 of the fish used the bypass system for downstream migration whereas 1/3 took the passage through the turbine. 38 fish were killed in the tests and 10 more were injured and it was questionable whether they would have survived in the nature. As can be seen from Table 1 almost two-thousend fish were tested but only a small percentage was killed in the turbine which made it difficult to statistically analyze species and size dependent behavior.The figure to be considered for the damage potential of the concept must be the relation of killed or injured fish with respect to the number of fish that migrated from upstream into the downstream (facility mortality rate). Actually almost 7% of the fish migrating from the upstream into the downstream, the facility mortality rate, were injured or killed with quite some species dependent differences. It was obvious that the best swimmers, the salmonids and among those especially the trouts, showed the highest mortality rate wheras the bullheads showed only minor mortallities (2%). Also the linear increase of the turbine mortality with increasing fish length as reported in literature could be confirmed.

A very interesting and significant observation could be made related to the size-dependent probabilieties whether to use the provided bypass migration path or the dangerous migration path through trash rack and turbine. On the one hand side the probabilities of smaller fish are higher to be attracted by the flow to the turbine. On the other hand the probability of damage by the turbine is higher for longer fish. The interesting thing is that these two effects almost compensate and that the injury probability during downstream migration, whether over the bypass or through the turbine, remains therefore almost constant. In the pilot plant with its small turbine and the high rotational speed the resulting damage/injury rate is at 7% over all species and all size length categories, see Fig. 5. It should be stressed that all graphics related to injury or mortality rates and all the corresponding figures are valid fo fish smaller than 200mm. All larger fish are mechanically not able to pass the trash rack and therefore they are completely protected. If one now tries to upscale the above figures to real and therefore somewhat larger powerplants the injury and mortality rate would decrease due to the more favourable geometric and operational conditions, i.e. the increase of diameter and decrease of turbine RPM. For a plant with a 250kw turbine the overal mortality rate would be around 2% on the fraction of fish smaller than 200mm. Considering that from a fish population about 1/3 does a major migration a year and therefore only such individuals would be suject to injuries, the population wide mortality would be even considerably smaller. Therefore it can be summarized that the protection of fish from injuries or death is very high at the TUM-HSPP.

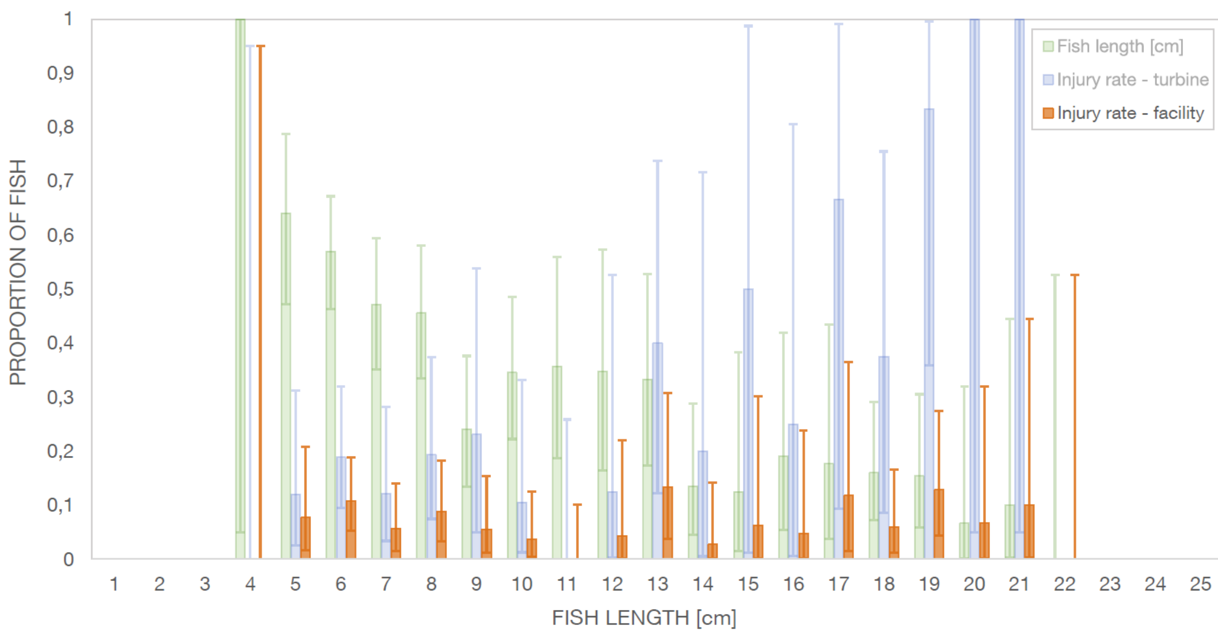

Figure 5: Length dependent probabilities for using the turbine passage (green) or the damage rate in the turbine (blue) and the size-independent resultant of these two effects (orange), Geiger et al. 2016.

4. The multi-shaft concept at a large river

If one tries to mitigate the impact of large hydropower on fish one could figure out to realize one or several TUM multi-shaft hydropower plants (TUM-MSHPP) instead of a conventional HPP. This idea has been investigated in a student’s thesis in more detail for the Mekong River. The scenario play tried to replace a large hydropower plant like e.g. the Xajaburi plant through 3 TUM-MSHPPs. A sketch of this idea is shown in Fig. 6. We expect from the tested downstream migration bypass, low mortality rates in the machines and considering the eco-migration corridors in the river axis and on both sides of the plant an unhindered upstream migration and therefore much smaller effects of HPP on fish populations. Additionally, a TUM-MSHPP concept would additionally be more compatible for the ecology because of sediment issues. All sediments larger than some 20mm are transported over the trash rack into the downstream and all smaller diameters are flushed through the turbine into the downstream. With heads of smaller then 10m the velocities of such sediments are low and the erosion damage to the turbine blades can be handled. Reservoir sedimentation of large hydropower plants is not only an operational and therefore economical issue in the vicinity of a plant but the capture of almost all sediments in a reservoir heavily affects the river in its downstream section. Habitat conditions for fish may change and depth and bank erosion will occur having impacts on the natural environment, on civilizing infrastructure, on irrigation and drinking water issues among others.

Of course the question arises how the construction of three smaller plants would affect the economy of a project and whether the economy of scale would heavily support a conventional design. Applying size dependent average costs of hydropower plants and accounting for a cost reduction of the multi-shaft concept of 30% compared with a conventional plant, according to our experience this is a reasonable reduction due to the much lower concrete use and the very simple concrete works, a financial sensitivity analysis has been performed. The results are slightly in favour of a classical design but depending on the prices for energy and the interest rates the result could also swap. Apart from that the analysis has not considered secondary effects and costs as indicated above. If such would be considered, if reservoir sedimentation would be financially taken into account and if fish population effects would be economically quantified the TUM-MSHPP would certainly be more economical then a classical large HPP. To be honest it also has to be stressed that it is presently unrealistic to realize a multi-shaft concept at very large rivers. The experience with the TUM-HSPP concept has to be transferred to the first plant at a real river which will happen within the next year hopefully. Then multi-shaft plants at smaller rivers had to be built and experience must be gained while turbine manufacturers would increase the size and power output of their completely dived turbines.

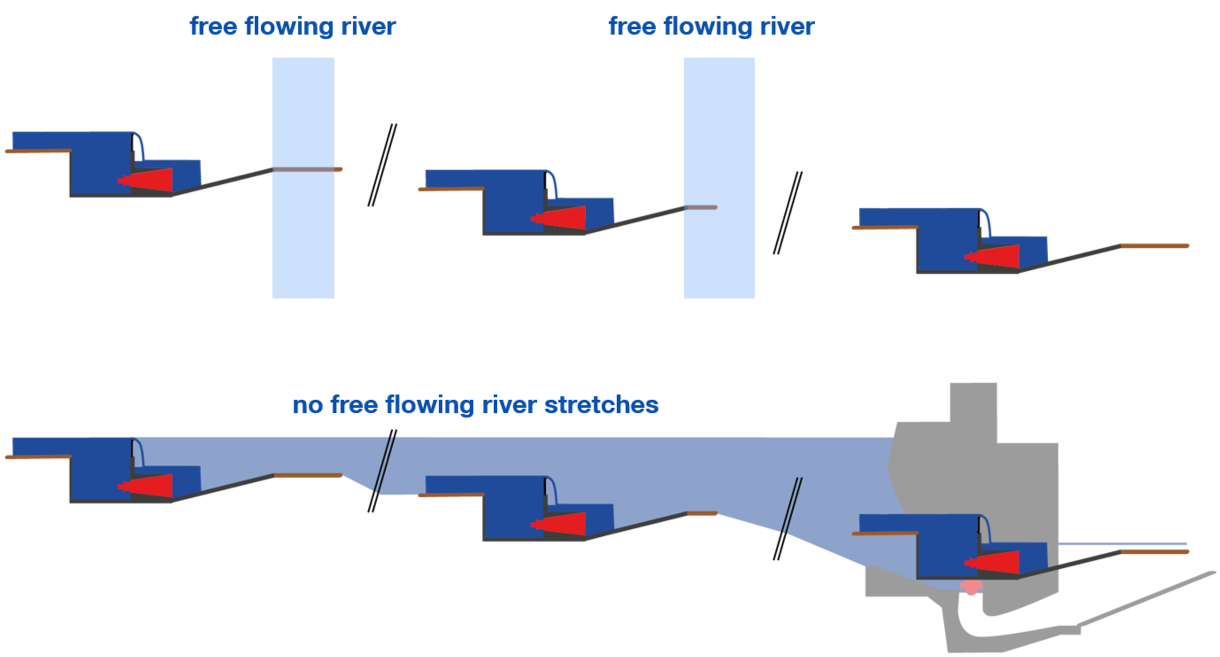

Figure 6: A comparison of a large classically designed HPP with three TUM-MSHPPs (Grönitz, 2015).

5. Summary and conclusions

The TUM hydro shaft concept is a promising concept with respect to costs, efficiency and eco-compatibility. The eto-hydraulic tests showed that fish are very well protected with the narrow bar spacing and the horizontal position of the trash rack working as a fish behavioural barrier. Furthermore, and due to the lateral and central eco-migration corridors also upstream migration of fish is optimal and not hindered. The concept has also proofed its ability for sediment transport from the upstream into the downstream and therefore reservoir sedimentation is not occurring. However, the current paper describes only a vision for future hydropower. Nevertheless, such visions should be followed as classical HPP designs have shown disadvantages to the environment which later had to be compensated. Therefore, not the economy of the pure construction only has to be considered but also the economy under sustainable long-term aspects. The sustainability with respect to the plant itself, to reservoir sedimentation issues, to aquatic populations and to civilized infrastructures supports considerably the presented TUM hydro shaft and multi-shaft concepts.

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The Authors

P. Rutschmann studied civil engineering at the Swiss Federal Institute of Technology (ETHZ), Zurich, from where he got his engineering diploma. He then worked as a research and senior research engineer at the Laboratory of Hydraulics, Hydrology and Glaciology of ETHZ. His PhD was an experimental work on spillway chute aeration devices. As an "Oberassistent" he later was responsible for the student's education in hydraulic engineering of ETHZ. After shifting to numerical modelling he became professor at the University of Innsbruck from where he changed as a full professor to the Technische Universität München (TUM). He is currently director of the Chair of Hydraulic and Water Resources Engineering, the Oskar von Miller Laboratory (hydraulic engineering) and the Dieter Thoma Laboratory (hydraulic machineries) of TUM.

S. Schäfer graduated 2012 as M.Sc. in Civil Engineering at TUM. He then joined Bilfinger SE a leading internationals engineering group. Later he started as a research engineer at the Hydraulic Engineering Chair. He currently conducts a PhD research work on sediment management in reservoirs, using both physical and numerical models.

A. Sepp graduated as civil engineer with a diploma from the University of Applied Sciences. He worked in an engineering company and also as a private engineering consultant. Later he became a research engineer at TUM while maintaining his private hydraulic engineering and mainly hydropower consultancies. He is the inventor of the TUM Hydro Shaft concept which he market-readily developed. He also acted as supervisor of the master thesis by N. Grönitz.

N. Grönitz graduated in 2015 as M.Sc. in environmental engineering of TUM. During her master thesis work she investigated the use of a TUM-MSHPP for the Mekong River. After earning her degree at TUM she left the university and works now as a professional engineer.

F. Geiger earned his diploma as physicist at the Ludwigs-Maximilian University (LMU), Munich with a thesis on cavitation erosion measurements. He started then as a research engineer at the Chair of Hydraulic Engineering of TUM. He is conducting further research in the field of cavitation but in parallel got involved into etho-hydraulic investigations with the TUM-HSPP. He soon will finish his PhD on the etho-hydraulic investigations. He earned all necessary qualification to conduct animal experiments with fish.