2.2 River power plants

[Th. Strobl, F. Zunic]

Hydroelectric power plant (HPP) is a generic term and includes all facilities where electric energy is produced by means of water power. It is not always easy to integrate a special power plant into the varying classifications known in literature. For a better understanding of the common classifications it is useful to define the different types of water power plants. In this section we will deal with *river power plants*, which under normal conditions belong to *low pressure power plants*. Contrary to this, *reservoir power plants* will be described in Sect. 2.3. Those facilities belong to *high pressure plants*.

2.2.1 Types of river power plants

There are a few different classification types where river power plants can be included. The most common classifications are by

- storage capacity,
- pressure head and
- installed capacity.

Other classifications refer to the layout of the power plant and its positioning within the river bed (see Sect. 2.2.2) or in a diversion canal (see Sect. 2.2.3).

2.2.1.1 Storage capacity

Although most HPPs are located on or near a creek or a river, one has to distinguish river power plants from storage plants or reservoir power plants. The term *storage* generally refers to a reservoir that has seasonal regulation capabilities. Because of the large volumes that can be stored in the reservoir, the inflow into the reservoir does not correspond to the discharge flowing through the turbines. Instead, according to the current demand of electric energy, the power is produced when it is needed. Thus, the electric power can be sold as peaking power, which is worth more and covers the peak demands on several hours of a day.

At river power plants there is no usable storage in the reservoir. Power production at any time is directly coupled with the current discharge in the river. Normally, the reservoir has a constant water level (full supply level), only rising to a small extent (maximum water level) when floods are passing the HPP. Therefore these water power projects are also called *run-of-river projects*.

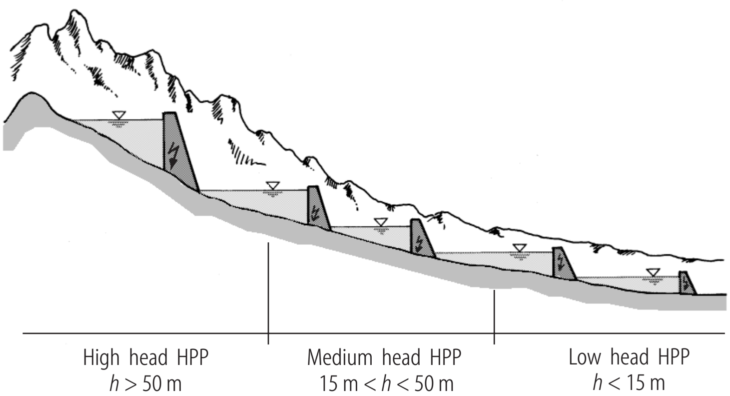

Fig. 2.2.1. High head, medium head and low head power plants.

In some cases, especially at larger rivers, the reservoirs have a small amount of storage capability. This can be used to adjust turbine discharges to follow daily or weekly demand patterns. Daily and weekly storage at a run-of-river is referred to as *pondage*, and the use of pondage permits a HPP to serve peaking power demands.

2.2.1.2 Pressure head

Contrary to high pressure HPPs with a head of over 50 m, low-head power plants possess only small heads of less or equal 15 m. The range between 15 and 50 m is covered by medium-head power plants. Most authors stick to this more or less arbitrary definition (Fig. 2.2.1).

Regarding these definitions, river power plants belong to middle pressure and low-head power plants, although there are some exceptions such as the Itaipu HPP with a head of 180 m and the Chinese Three Gorges HPP at the Yangtze River with a head of 175 m and an installed capacity of 18000 MW (see Sect. 2.4). Because of their size and their design, both facilities could also be assigned to reservoir type power plants and, per definition, to high-head plants.

2.2.1.3 Installed capacity

The installed capacity naturally varies depending on the available discharge and the head at the facility. Power plants with an installed capacity of less then 5000 kW are called *small hydro power plants*. Although they contribute only little to the overall energy output, they play an important role as a reliable energy supplier. Power plants with an installed capacity between 5000 kW and 100 MW are middle range facilities, whereas major HPPs have an installed capacity of more than 100 MW.

2.2.1.4 Other definitions

Generally, a single power plant does not produce energy directly for a nearby community or industrial facility. Instead electricity is fed into the regional electric network of the operating company. In this way, several power plants are connected in compound operation. Only rarely, e.g. in secluded regions, is a HPP running in single mode operation.

In many cases a river power plant serves not only for power generation. When the facility is located in the vicinity of a city, the storage lake is often used as recreation area and for sporting activities. Sometimes the reservoir is also needed for low-water elevation during dry periods or it is used for flood protection. In case of utilization besides energy supply, a power plant is a *multipurpose utility*.

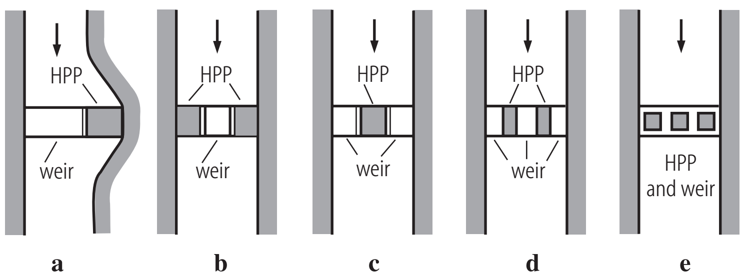

Fig. 2.2.2. Layout of power house and weir within the river bed.

Fig. 2.2.3. Bay power plant HPP Vohburg at the river Danube (Bavaria).

2.2.2 Positioning river power plants

Depending on the topographic situation at the river-site where a HPP is planned, there are several possibilities to locate the power house (Fig. 2.2.2). A widespread layout is to place the power house into an artificial bay at one of the river banks, see Fig. 2.2.2(a). This construction is always necessary if the facility including all auxiliary buildings (weir, sluice) is too large to fit between the natural river banks. This type of a block power plant is also named *bay power plant*. The most important advantage of this layout (a) is the optimal passage of floods at the weir adjacent to the power house (Fig. 2.2.3).

Under circumstances the width of the river is large enough to place all buildings including the weir into the original river bed without affecting flood passage. In this case, one has several possibilities to place the powerhouse relating to the weir. Especially when a power plant is planned by two countries as a joint venture located at a border river, option (b) is suitable. Each country can run its own plant without interfering in the operation of its neighbor. Because of inconvenient accessibility of the power house, layout (c) is only recommended when foundation conditions call for this location. A widespread arrangement is option (d) where every single turbine along with a coupled generator is placed into a separate pier of the weir. In this case the units are accessible by a bridge crossing the river. Option (e) of Fig. 2.2.2 represents a power plant that is completely overtopped by the river discharge. Ecological and landscape aspects sometimes lead to this design, which certainly is not very convenient in operation.

In river bends the power station is located at the outside curve because of the so-called spiral flow. In rivers with sediment transport, this rotating current leads to erosion of the outside curve and to silting of the inside parts of the river bed (Fig. 2.2.4). Hence, to protect the intake structure of the power house from silting, it has to be placed at the outer river bank. Besides, a continuous discharge with silty water would rapidly destroy the turbine blades.

The inflow to the turbines must be optimized to gain high effectiveness in power generation. Therefore the optimal flow against the intake structure is of great importance. The separation pier between the powerhouse and the weir has to be designed in a way that energy-losses are minimized. Figure 2.2.5 shows a construction with a combination of varying circle-curves. In most cases, though, a shaping of the front side of the separation pier as a half-circle will be sufficient.

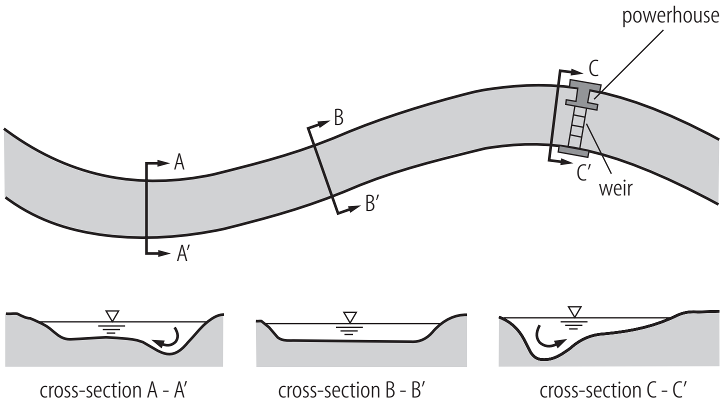

Fig. 2.2.4. Development of the spiral flow in river bends.

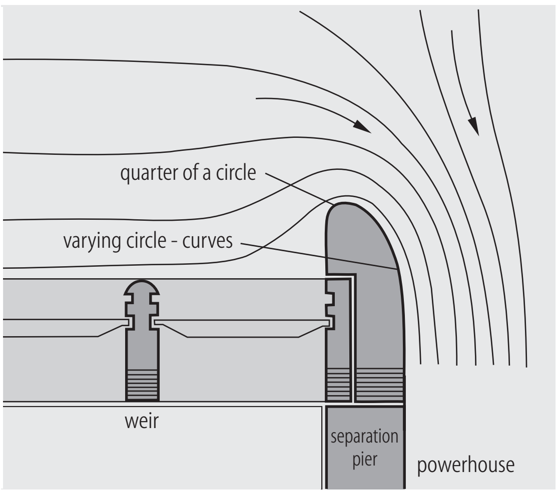

Fig. 2.2.5. Construction of the separation pier between powerhouse and weir.

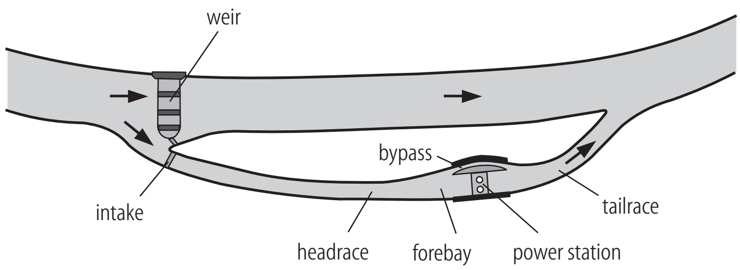

Fig 2.2.6. General layout of a diversion power plant.

2.2.3 Diversion canal power plants

Sometimes there are difficulties to place a power plant into the river bed, for instance because of ecological aspects or simply due to lack of space. In this case a proper alternative is the construction of a diversion canal, placing the powerhouse within an artificial canal (Fig. 2.2.6). One of the advantages of this type of construction is the possibility to erect the plant in a foundation ditch away from the river bed. Another merit is the higher energy output due to shorter flow-length with considerably less friction losses. Besides, the energy losses can be minimized by lining the channel with smooth materials like concrete cover or asphaltic concrete. And, of course, there is almost no disturbance in operation by passing floods which flow through the main river bed as before.

Especially when rivers are meandering a lot and have only little mean discharges, a diversion canal plant is a good choice, because it avoids ecological disturbances like oxygen depletion which could occur in the storage lake of conventional plants due to rising temperature as a result of slow flow velocities. This would not take place to the same extent within the headrace of a diversion plant, because it is usually developed as a narrow channel.

2.2.4 Components of hydroelectric plants

A hydroelectric power plant consists mainly of the power station and some auxiliary buildings like the weir, which is necessary to bank up the water thus creating the needed head and – in case of a navigable river – a sluice to maintain navigation. In this section we will have a closer look at the power station, and Sect. 2.2.5 will deal with these auxiliary constructions.

2.2.4.1 Power house

A typical longitudinal section of a low head power plant is shown in Fig. 2.2.7. The corresponding cross section of the same HPP including the weir construction is presented in Fig. 2.2.8. The main components of the power station are the intake structure, which is enclosed by the separation pier (5) and the abutement sidewall. Before entering the penstock, the water passes through a rake (4) which keeps back deposits and waste. The heart of the facility is the turbine (2) and the generator (1). In case of a bulb turbine or tubular turbine like in Fig. 2.2.7, which actually is a Kaplan turbine with a nearly horizontal axis, the generator is housed by the bulb. Usually the axis of the turbines is vertical so that the generator can be placed securely against flooding in the power house. After passing the turbine blades, the water flows through the draft-tube (3) before it reaches the tailrace of the plant. Figure 2.2.9 shows a cut open model of the installed bulb turbine.

Within the power house, all the electric controlling means are installed which are needed to run the facility including the control of the weir gates. Besides it contains several workrooms, sanitary rooms and the offices for the staff. The transformer station is located outside of the power house. From there, the electric power is fed into the electric network. Figure 2.2.10 shows a common version of a Kaplan turbine with a vertical axis.

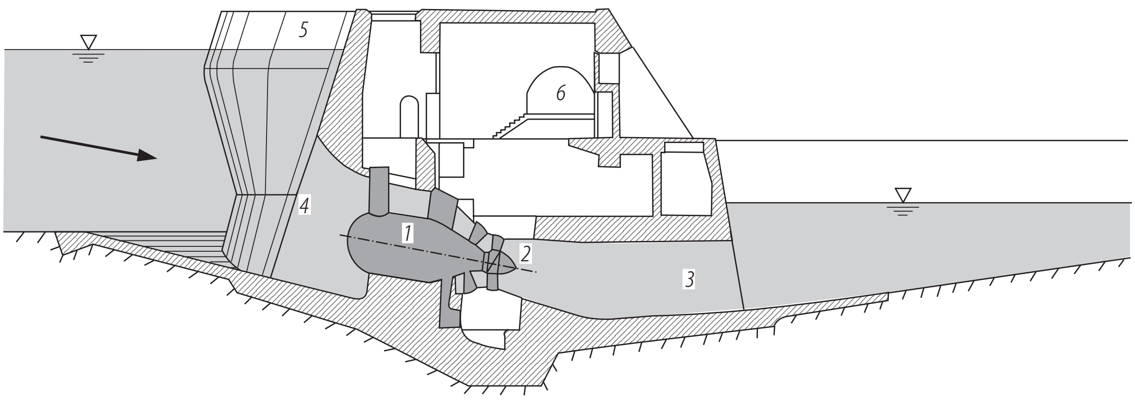

Fig. 2.2.7. Longitudinal section of the HPP Merching on the river Lech (flat axis Kaplan turbines) [84BLW].
1 - bulb generator; *2* - turbine; *3* - draft-tube;
4 - rack; *5* - separation pier; *6* - weir gallery.

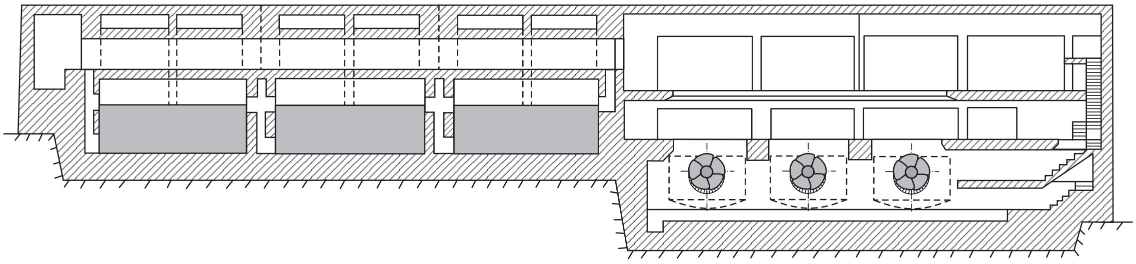

Fig. 2.2.8. Cross section of the HPP Merching with a weir (left) and the power house with turbines (right) [84BLW].

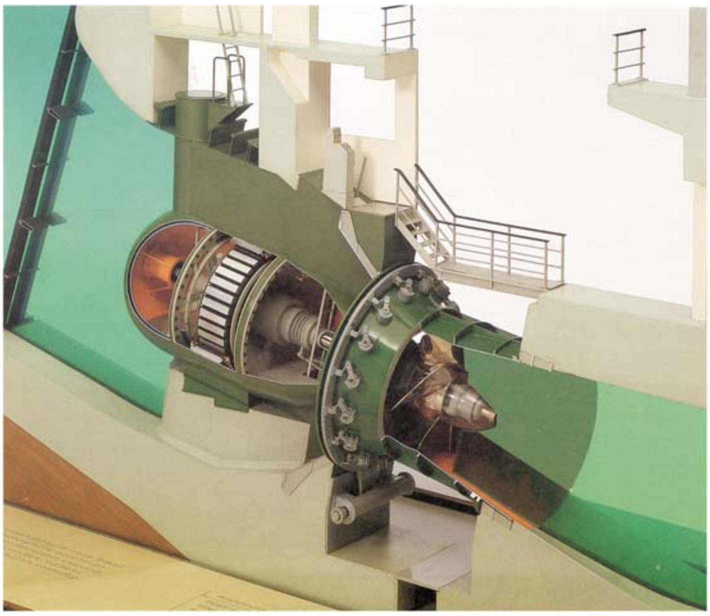

Fig. 2.2.9. Spatial view of a bulb generator (cut open model).

2.2.4.2 Turbine layout

An optimal layout of the turbines is crucial for the amount of energy one can produce with a river power plant. Since hydraulic turbines will be subject to a detailed discussion in Sect. 2.7, only a few basic principles of turbine characteristics and layout will be mentioned here. Modern turbines work within an efficiency range of about 90%. Combined with a likewise high efficiency of the generator, one can assume that the output of a modern water power facility is about 85% of the primary energy of the flowing water. No other energy source disposes of such a high degree of energy output.

The general design of the intake structure, the outline of the turbine and the shape of the draft-tube is shown in the following figures. Figure 2.2.11 shows a Kaplan turbine with a vertical axis and Fig. 2.2.12 sketches out a Kaplan turbine with a horizontal axis. All extents are given in relation to the diameter d_1 of the turbine wheel. For an initial sketch of the turbine layout, these specifications should be appropriate. Some corrections of the first draft might be necessary because of special local conditions at the building site. Figures 2.2.7 and 2.2.10 show built constructions of the two Kaplan-type turbines. In contrast to the general sketch in Fig. 2.2.12, the power plant in Fig. 2.2.7 houses a Kaplan turbine with a slightly inclined axis.

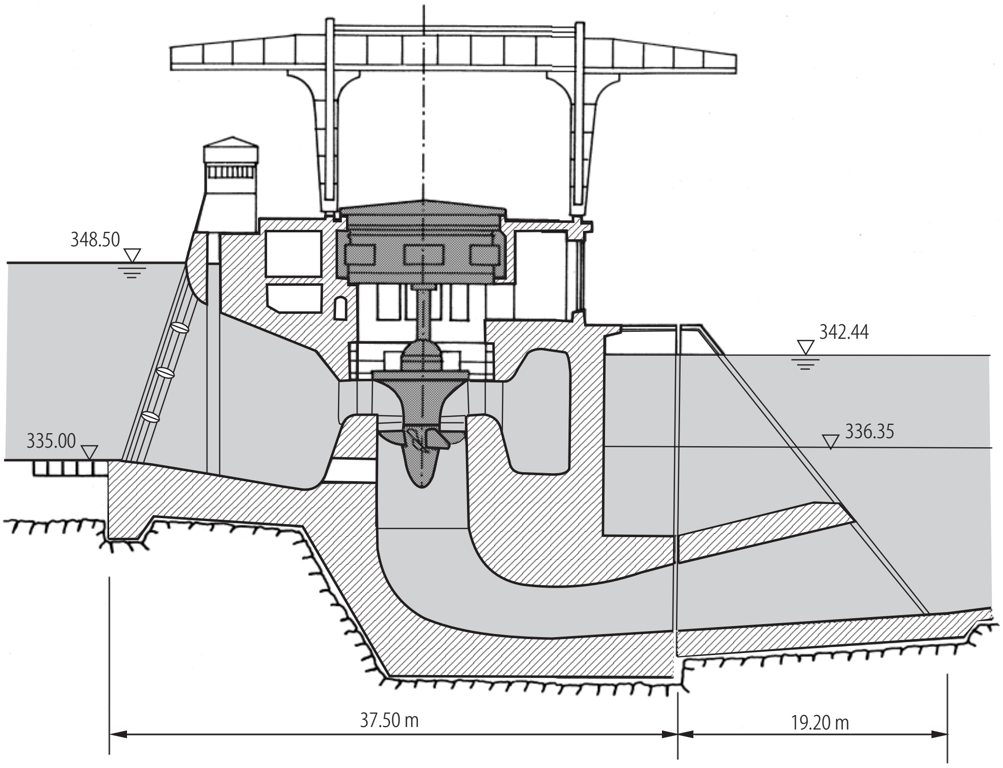

Fig. 2.2.10. Kaplan turbine with vertical axis installed in a power house.

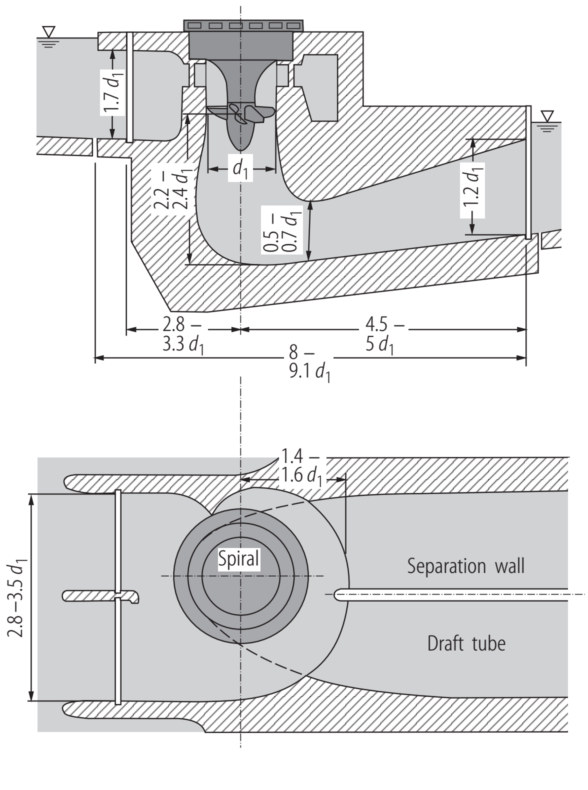

Fig. 2.2.11. General layout of a Kaplan turbine with a vertical axis.

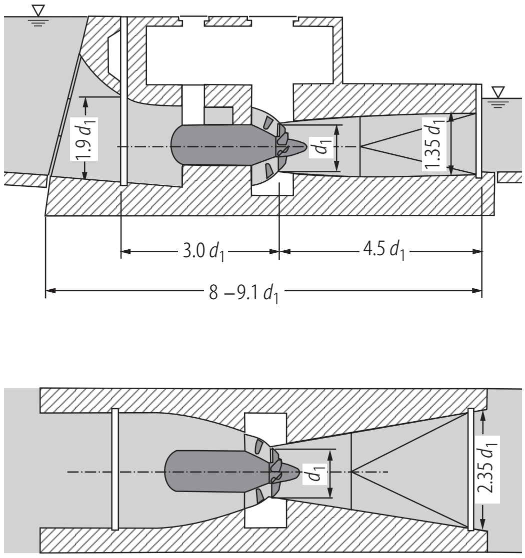

Fig. 2.2.12. General layout of a Kaplan turbine with a horizontal axis.

2.2.4.3 Cavitation

Cavitation is often described as the boiling of a liquid at constant temperatures but low pressures. Vapor-filled bubbles result from a reduction of the pressure p lower than the vapor pressure p_v, caused by high flow velocities or in the centre of vortices. These bubbles are transported by the flow to zones of higher pressures with an abrupt bubble collapse. Cavitation causes several negative effects in hydraulic machinery and hydraulic structures, e. g.

- loss of efficiency,
- vibrations and noise emission or
- material erosion.

In river power plants cavitation can cause problems especially to turbine runners (Fig. 2.2.13) and to stilling basins (concrete erosion). In the case of reservoir power plants, structures like bottom and service outlets or spillways are endangered, too.

The flow in a turbine is obviously complex. To estimate a turbine's cavitation performance, the Thoma-number σ_T is the accepted parameter:

$$\sigma_T = \frac{H_a - H_v - z}{H},$$

where H_a is the atmospheric pressure head, H_v is the vapor pressure head, H is the gross head of the turbine (neglecting energy losses) and z the elevation of a turbine reference level above tail water level (see Fig. 2.2.14). Each type of turbine will cavitate when operated at a value of σ_T lower than a certain (empirical) critical value $\sigma_{T,C}$ (Fig. 2.2.15). So it would be possible to avoid cavitation by putting the turbine on a low level z. However, this is expensive in terms of excavation, so it is not unusual to allow some cavitation and accept the risk of erosion. In doing so, cavitation erosion in turbines can be reduced dramatically by injecting air.

Cavitation performance of turbines can be improved by the design of the runners. The prediction of cavitation performance of the runners is often derived from model tests in cavitation test facilities. For transferring the test results to prototype conditions, there are two main categories of scaling issues: the water quality with regard to its cavitation susceptibility (tensile strength) and scale effects, i.e. for velocity, size, turbulence, viscosity etc. These scaling issues refer to both cavitation inception [01Kel] and erosion [01Hub].

Fig. 2.2.13. Cavitation erosion on a turbine runner.

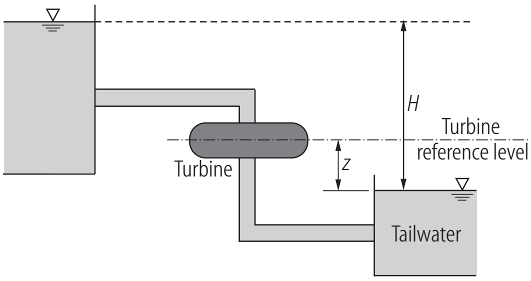

Fig. 2.2.14. Definition sketch for Thoma-number σ_T.

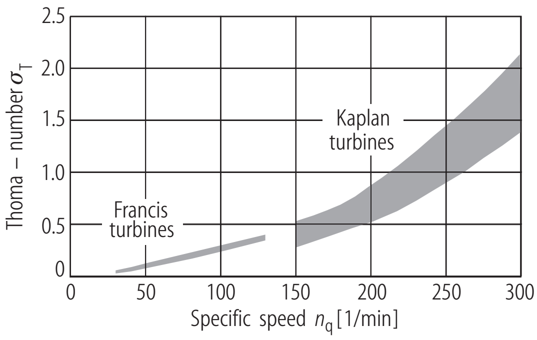

Fig. 2.2.15. Critical values $\sigma_{T,C}$ of the Thoma-number for different types of turbines [98Gie].

2.2.5 Auxiliary Buildings

Every hydro power plant consists of several auxiliary buildings. The most common are a weir and a sluice. Sometimes small boat slides are installed to make it possible for sport boats to pass the weir without using the lock, which then is only used by navigation. To enable fishes to migrate, fish-passes are located mostly at one side of the river, either as a concrete structure or within a diversion channel. The problems with fish-passes are discussed in detail in Sect. 2.2.6.2.

2.2.5.1 Weir

As every hydro power plant is built at a river or even within the river bed, one has to consider the characteristics of the discharges, especially of the floods. As a general rule, the undisturbed passing of floods has priority. As mentioned before, the weir dams up the water to provide the needed head for power generation. So the weir is to be constructed in a way that with open gates, the flood causes no damage both to the hydro power plant and, of course, the environs.

The German standard, for example, claims that a flood with a recurrence period of 100 years is to be considered for weir systems (DIN 19700, part 13). In the so-called (n-1) condition, it is stated that the dimensions of a weir with controlled gates must generally be large enough for the flood to pass through the weir without damage, even if one of the gates is blocked. This means that the storage level must not be exceeded even if one gate could not be opened. It is self-evident that in case of weirs with several fields of different widths, the passage with the largest discharge is assumed to be closed.

As mentioned before, optimal flood passing is ensured when the weir is situated in the main axis of the river flow. Each construction element of the weir must be designed in a way that it is no obstacle to the flow. Therefore the weir piers are shaped as a half-circle at their upstream end. The abutement sidewall (see Fig. 2.2.16) consists of a wall that is formed like a quarter of a circle at the upstream side and like a quarter of an ellipse at the downstream end. Such a layout allows the flow to contract without major eddies and without separating from the wall. The embankment near the sidewall is paved with large stones to protect it from erosion. Figure 2.2.16 shows the basic construction rules which can be applied to most facilities.

During normal operation the weir sections are closed by gates, for instance radial gates, flap gates or sector gates. A widespread solution is the combination of a radial gate and a flap gate on top.

2.2.5.2 Sluice

At navigable rivers, each hydro power plant consists of a sluice which maintains navigation. In most cases, the sluice and the navigation locks are situated at one of the river banks opposite of the power house. Figure 2.2.17 shows an example with a sluice at the right side and the machine hall at the left side of the Tisza River in Hungary. The weir is situated in the middle of the river bed for optimal flood passing.

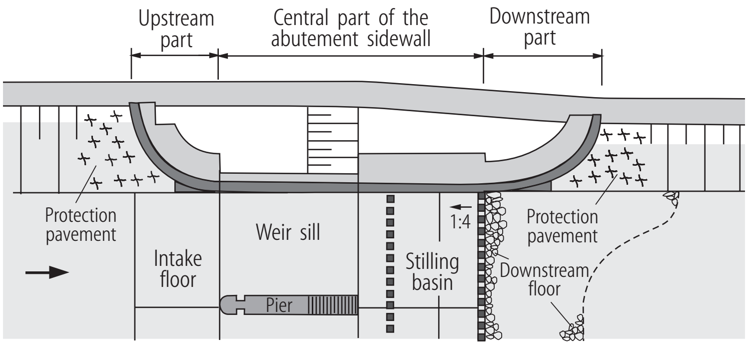

Fig. 2.2.16. Principal construction elements of a weir and the abutement sidewall in plan view.

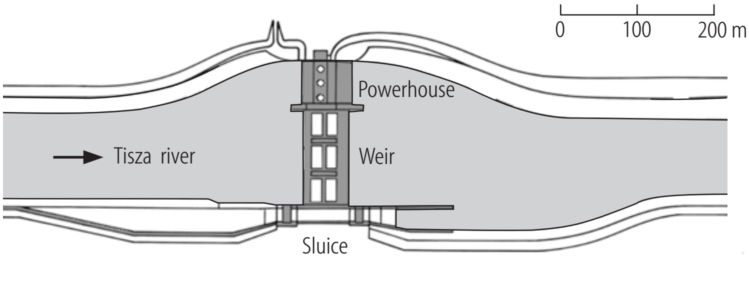

Fig. 2.2.17. Example layout of the power house, weir and sluice at the Tisza River in Hungary.

2.2.6 Ecological aspects of hydro power plants

Without doubt, the use of hydro power is one of the most efficient and one of the few sustainable ways of producing electricity. It also contributes to CO_2-free energy without polluting the atmosphere or producing waste. Therefore, the need of building power plants is undisputed. Nevertheless there are interferences with the natural balance. Each facility disturbs the local fauna of the river bed by changing the characteristics of the flow. Often microorganisms and fish have no chance to pass the facility. Therefore one has to consider the ecological aspects of a hydro power plant already in the planning stage.

2.2.6.1 Residual flow

In diversion-type canal power plants, almost all the water is diverted at the weir to the intake structure of the power canal. Little or no discharge, the so called residual flow, remains in the main river bed. The effects of a reduced or even insufficient flow of water within the main river have been discussed with great interest during the last few years. The growing sense for ecological problems meanwhile led to a more critical attitude towards hydropower. The key-question is: *"How much water should remain in the riverbed to guarantee satisfying conditions for the biotic community?"* To answer this question, the so-called *MEFI-model* [95Hei] was developed at the Technische Universität München in Munich in order to determine an ecologically-founded minimum discharge for any residual flow reach.

The biotic community of a watercourse, governed by extremely complex interactions of numerous factors, reacts most sensible to changing discharge conditions. Extensive investigations of hydraulic, morphological, biological, physical and chemical parameters in residual flow reaches as well as in virtually unaffected flow reaches at more than 25 hydro power plants in the upper and middle reaches of several mountain rivers in Bavaria showed that near bed flow conditions, the roughness of the river bed and solar irradiation are the most important parameters for characterizing ecological conditions in a watercourse, each of them including additional influencing parameters as shown in Table 2.2.1.

In order to determine the residual discharge using the MEFI-model, flow conditions at different discharge-levels at characteristic flow cross-sections have to be surveyed in the residual flow reach. At each cross-section and actual discharge, the bottom roughness on the basis of the mean height of the algal

Table 2.2.1. Parameters for characterizing ecological conditions in a river.

Measured parameters	Included parameters
Near bed flow velocity u_{nb}	discharge gradient river bed morphology bottom substrate grain-size distribution (bottom roughness) nutrient supply turbulence
Bottom roughness h_{A50}	gradient intensity of near bed turbulence near bed flow velocities availability of habitats
Degree of solar irradiation *IF*	bank vegetation nutrient supply water temperature algal growth water chemistry (e.g. oxygen content, pH-value)

growth h_{A50} and the mean flow velocity near bed u_{nb} have to be determined. Combining these parameters yields the relationship between discharge and the near-bed Reynolds number Re_{nb} which is individual for each residual flow:

$$Re_{nb} = \frac{u_{nb} \cdot h_{A50}}{\nu}.$$

With the mean low water discharge Q_M the near-bed Reynolds number can be determined (Fig. 2.2.18). 50 per cent of this value (Re_{nb50}) leads to the base discharge Q_B.

Re_{nb} is also closely related to the number of Taxa_{rheo} (Fig. 2.2.19). This biological parameter, representing the ecological conditions, includes organisms which require high water quality, a river bed comprised of coarse material (e.g. gravel) and a certain minimum flow velocity [97Mai]. The undisturbed biotic community of the investigated rivers is comprised of a high percentage of rheo-typical organisms which serve as an indicator for good ecological conditions in the investigated residual flow reach. Linking these two relationships allows a prediction of Taxa_{rheo} that can be expected at a certain discharge level and consequently the discharge necessary to fulfill the requirements of the biotic community.

For the determination of the necessary residual flow, the value of Re_{nb} corresponding to the mean low water discharge Q_M has to be determined first (Fig. 2.2.18). In the example considered, the value of Re_{nb} at Q_M = 2.16 m³/s is 3215. The discharge corresponding to a particular percentage of Re_{nb}, empirically defined as being 50% (yielding Re_{nb} = 1607), is taken to be the base discharge Q_B for the residual flow reach (here: 0.37 m^3/s). Q_M was chosen to represent a river-specific characteristic parameter, as the values of Q_M lie in the sensitive region of the Re_{nb} vs. discharge-curves. The value Re_{nb50} used to determine Q_B represents a value which has proven to yield realistic results in all past investigations.

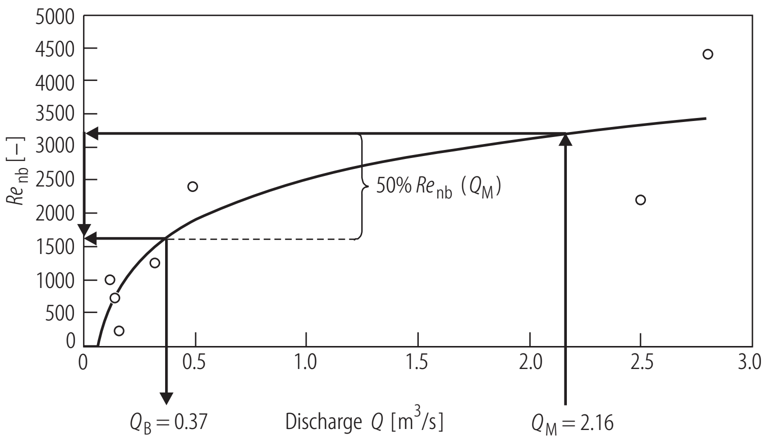

Fig. 2.2.18. Relation between discharge Q and Re_{nb} and determination of the base discharge Q_B (Weiße Traun River in Upper Bavaria).

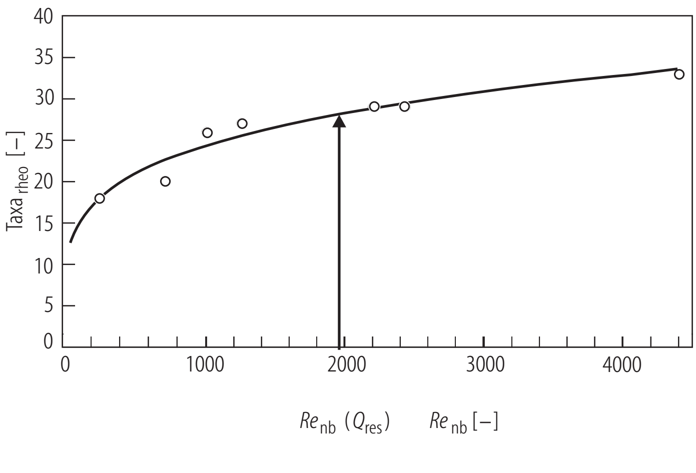

Fig. 2.2.19. Relation between Re_{nb} and Taxa_{rheo} at Weiße Traun River.

Especially in case of low water depth and low velocities, high solar irradiation can lead to an excessive increase in water temperature and consequently cause harmful algal-growth. These negative effects only occur when the degree of solar irradiation exceeds a certain value, a moderate amount of sunshine is certainly desirable. An especially developed irradiation factor *IF*, describing the intensity of solar irradiation, takes the negative effects of an increasing water temperature into account. In case of high solar irradiation the base discharge consequently has to be increased:

$$Q_{\mathrm{res}} = Q_{\mathrm{B}} + \frac{Q_{\mathrm{B}} \cdot IF}{10} \, .$$

In the example considered, $IF = 4.72$ leads to $Q_{\mathrm{res}} = 0.37 + (0.37 \cdot 4.72 / 10) = 0.545$ m³/s. On the basis of the measured biological data it is possible to check the ecological efficiency of the minimum discharge level determined with the MEFI-model (see arrow in Fig. 2.2.19 corresponding to Q_{res} including additional discharge due to solar irradiation) and to choose the residual flow in a way that hardly any reduction in the diversity of species has to be expected. As shown in Fig. 2.2.19, a further increase in the ecological efficiency would require a disproportionate increase in discharge.

The MEFI-Model, although it only takes near bed flow-conditions into consideration, provides a possible means to determine an ecologically founded minimum discharge level in residual flow reaches of small hydro power plants. In addition to its general applicability, the model's main advantages are that no large-scale investigations are necessary as well as its low time and cost requirements. It can be applied during the planning phase of the power plant and guarantees a high correlation with river biology.

2.2.6.2 Fish passages

The construction of hydropower plants may result in unpleasant side effects to the ecosystem. Besides the changing of flow conditions, one major problem associated with the installation of river plants is the interruption of the continuous watercourse. There is no possibility for upstream migrating fish to pass without fishways in place. Concerning this problem, a lot of solutions for upstream movement have been offered during the last decades. Meanwhile many plants provide upstream fishways, either technically or naturally-like designed.

On the other hand, there is usually no opportunity of passage for downstream migrating fish. So, they are forced to pass the turbine or the weir in time of floods in order to change their habitats or to reach the ocean for spawning. A lot of international investigations during the last years showed that passage through turbines may result in considerable mortality rates. A variety of fish protection facilities, especially for juvenile species like smolts, have been developed in order to overcome this problem. Great measures have been implemented in the Northwest of the USA and Canada although these facilities are usually unsuitable concerning other katadromous species like the European Eel.

At present there is a lot of research starting in North America and Europe to get more information on natural migration and to find solutions for downstream passage of adult eels on their way back to spawning habitats in the Atlantic Ocean. Therefore various ways are discussed. Besides the idea of undamaged passage through fish friendly turbines and the opportunity of turbine close down and passage through the weir, special attention is given to the development of downstream bypass facilities. A downstream passage facility consists of several components such as the intake, preliminary guiding and collection facilities for diverting fish. If necessary, different kinds of barriers to block the turbine intake can be installed. Therefore behavioral barriers, for example based on light or sound avoidance, or physical barriers like wedgewire screens can be used.

The simple blocking of turbine intakes by screens in order to prevent fish from passing the turbines cannot be a final solution. Despite decreasing turbine mortality rates, this is no solution for downstream passage. A general layout for a fish bypass, suitable for both directions, up and downstream, is shown in Fig. 2.2.20. The bypass system consists of a natural-like diversion stream providing observation facilities. Compared to single upstream fishways, the added water of the downstream way increases the effect of attracting upstream migrating fish. To induce downstream migrating fish to use the bypass, guiding and collection facilities have to be added to divert fish more effectively. Optional physical or behavioral barriers can be installed to screen the turbine intakes from entering fish.

In conclusion, there is to say that a longitudinal connection of the river has to be an objective in the future. Especially for katadromous downstream migrating fish, the opportunity of undamaged passage is essential for their life cycle. It has to be remarked that the side effects to fish passage can reduce the acceptance of water power as a renewable energy. Therefore, it is a commitment for science and companies to redress this drawback in the near future.

2.2.6.3 Effects on the groundwater table

By damming up water, to partially considerable heights, the groundwater level in the vicinity of hydro power plants can be influenced. The undisturbed connection of groundwater and river is cut off by more or less impermeable sealing elements along the reservoir dams. As a result, the groundwater table can rise to a level where housing estates, agriculture and nature are affected. For this reason, small channels on both sides of the reservoir have to stabilize the existing groundwater table in the neighboring area. These channels receive the water possibly leaking out from the reservoir as well as the discharge from precipitation which now cannot reach the river directly. The caught water then flows downstream to the tailrace of the power plant where it can be released into the riverbed or has to be pumped into the river.

It is necessary to estimate the effects of river power plants relating to the groundwater table very carefully. Today, numerical models are used to estimate the influence of reservoirs to the groundwater behavior.

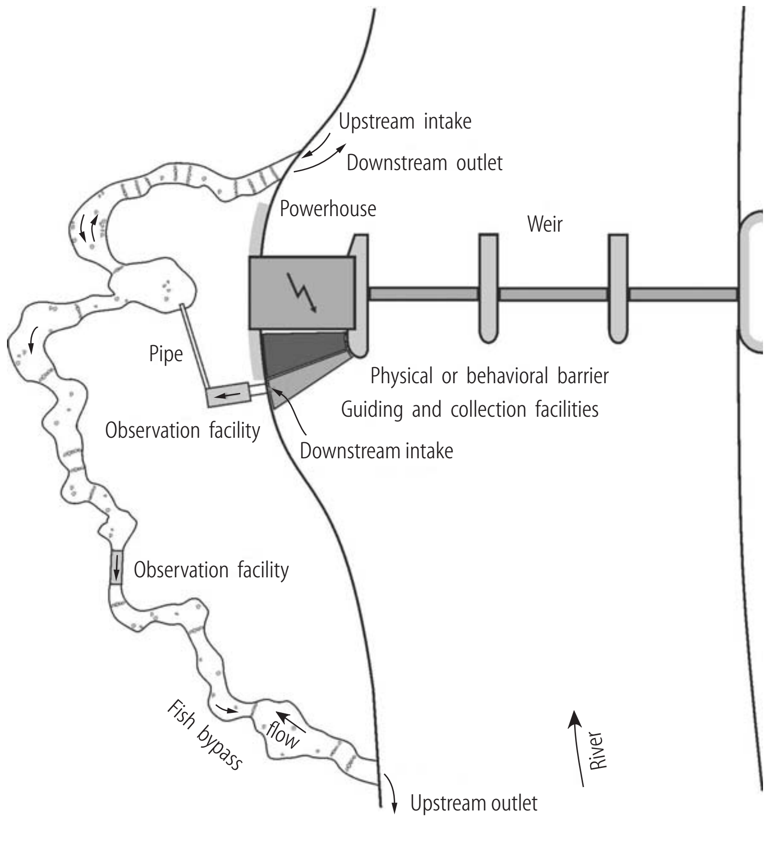

Fig. 2.2.20. Possible fish bypass for upstream and downstream migration.

2.2.7 References for 2.2

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