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Design of unstructured block ramps: A state-of-the-art Review

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Design of unstructured block ramps: A state-of-the-art review

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ABSTRACT: Block ramps are an alternative hydraulic structure to drops and sills for the stabilization of river beds. The absence of a vertical step together with acceptable flow velocities makes block ramps passable for fish and other species, while controlled energy dissipation can be achieved. Two main types of block ramps can be distinguished. Type A, where the blocks are tightly packed, forming a block carpet. Type B is characterized by dispersed block clusters that are isolated or grouped in some geometrical configuration. Especially in the case of unstructured block ramps with single randomly distributed roughness elements (classified under type B), the hydraulic conditions are strongly heterogeneous and are difficult to describe. Certain approaches are available to characterize the flow conditions occurring on block ramps, often limited to a certain parameter range corresponding to certain experimental conditions. The aim of this paper is to outline the state of the art of the knowledge of physical processes, ecological requirements, structural stability, and existing design criteria on block ramps, with special focus on the unstructured block ramp design. Further research to improve existing design guidelines and to determine the ecological functionality for this type of block ramps is needed.

Keywords: Block ramp, Roughness element, Ecological network, State of the art, Design criteria.

1 INTRODUCTION

According to Zeh Weissman et al. (2009) Swiss water courses are interrupted by approximately 100’000 drops or sills with a level difference Δh larger than 50 cm. Such structures cannot be overcome by most of the fish or smaller species, which is inacceptable according to ecological requirements.

Block ramps are river engineering structures to gradually overcome height differences of the river bed while controlled energy dissipation can be achieved. Block ramps are more and more used in river restoration projects because of their ecological functionality. In the last decades many existing drops and sills have been replaced by block ramps and many more are planned. However, during the last flood events, it turned out that the design of the block ramps was not in all cases sufficient, as many of them failed (e.g. Bezzola and Hegg, 2008).

Ecological requirements for river engineering measures are becoming more and more eminent. Therefore, the applicability of block ramps is not just depending on stability criteria, but also on their ecological behavior, where structural heterogeneity and flow conditions (particularly water depth and flow velocity) are important. For that reason, research on block ramps has to progress towards two major aims at the same time: A) robust stability criteria, B) improved ecological sustainability.

The considerations given in the present paper assume conditions that are typical for Alpine regions, i.e. typical rivers slope S of approximately 1-10%, characteristic grain diameter d_{90} in the order of 5-30 cm, a wide grain size distribution ($\sigma = (d_{84} / d_{16})^{0.5}$ up to a value of 4 or 5) with relatively low submergence levels h/D (h = water depth, D = block diameter).

For block ramps built under Alpine conditions two different design manuals are available. Firstly, Hunziker, Zarn & Partner AG (2008) developed a manual to provide design and constructive guidelines for river restoration measures especially with block ramps. Maximal specific discharge q_{max}, block diameter D and grain characteristic of the bed material d_c are suggested, both for ramp types A and B. However, those parameters are mostly derived from experience and model experiments carried out at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) in Zurich. Thus the applicability of these guidelines is often limited to a certain experimental data range and certain test conditions. Design suggestions are mostly given in form of diagrams and tables. For block ramps of type A (Fig. 1), where the blocks are tightly packed forming a block carpet, the stability criteria given by Hunziker et al. (2008) are quite comprehensive. However, in the case of unstructured block ramps of type B (Fig. 1) important design criteria are still missing. For example, the interaction between block diameter and block placement density is unclear, as well as the influence of the relative submergence.

Secondly, a work group of the German association for "Wasserwirtschaft, Abwasser und Abfall" (DWA) presented guidelines (DWA, 2009) on naturally oriented block ramps. These refer also to unstructured block ramps of type B, and not only the hydraulic conditions, like flow resistance and stability criteria are examined, but also the ecological limitations and requirements are discussed in detail. DWA (2009) stated that the flow resistance of a block ramp is difficult to predict only by applying characteristic block diameters and grain size distribution of the bed material. Additional information on the bed shape, for example the standard deviation s of the height distribution of the roughness elements, is needed. However, a relation between parameters describing the bed material including the blocks and s is not available yet.

During the last 10 years, various research projects on step-pool systems and on block ramps both of type A and B were conducted at VAW (i.a. Weichert, 2006; Semadeni et al., 2004a and 2004b; Janisch et al., 2007; Tamagni et al., 2008). In 2006 a workshop on block ramps was held at VAW to outline the state of the art on block ramps with focus on ongoing research, existing design guidelines, environmental requirements, and to summarize practical knowledge (Minor, 2007).

Despite the recent progress in this research area, no universally valid approach, especially for the case of unstructured block ramps of type B, to characterize the flow and ecological conditions is available, due to the complexity of the flow processes (DWA, 2009). Therefore, the design of new block ramps, and the prediction of their stability and their ecological conditions is still limited. The aim of this paper is to give an overview of the different approaches as well as to outline the restrictions and the required assumptions (both hydraulic and ecological) to design block ramps, with particular focus on the unstructured block ramps of type B under Alpine conditions.

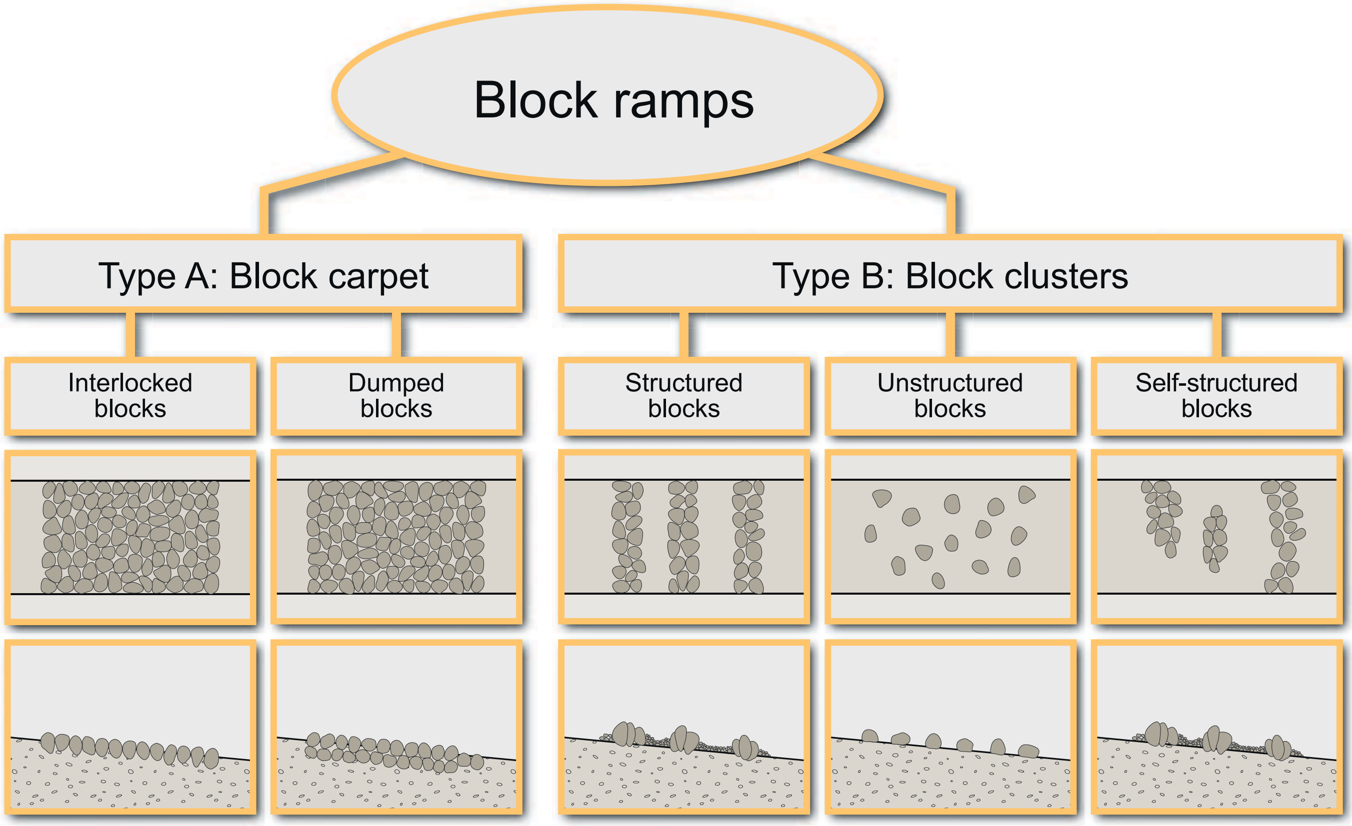

Figure 1. Classification of block ramps (Lange, 2007, modified).

2 VAW EXPERIENCE WITH BLOCK RAMPS

According to the classification given in Fig. 1, block ramps can be divided into two types: Type A includes the classic block ramp design, in which the blocks are tightly packed, forming a block carpet. The blocks can be carefully placed close together in one layer leading to interlocked blocks or randomly dumped in two or three layers. The main difference is the needed amount of blocks, which has a major influence on the costs. Another difference is that the effective roughness of a ramp with dumped blocks is slightly higher than in the case of interlocked blocks. Filter material is used to protect the underground material against washout effects (DWA, 2009). Experience with block ramps of type A shows that they are stable up to a slope of 10% (Bezzola, 2005). Regarding ecological aspects block carpets are very homogeneous in flow velocities and bed topography and therefore less preferable to distributed block clusters as in type B. All the three subcategories lead to much more natural conditions because of the more distinctive heterogeneous geometrical conditions

Type B block ramps are characterized by dispersed block clusters grouped in certain geometrical configurations (ramps with structured and self-structured blocks) or isolated randomly placed on the bed material with a certain density. The block placement density is generally defined as the ratio between the river bed covered with blocks to the total bed area. Self-structured ramps were studied within the research on step-pool systems, and are neglected in this paper.

For type B ramps the ratio between the block diameter D and the characteristic grain size d_{90} of the bed material is of particular importance. According to Raudkivi & Ettema (1982), the ratio D/d_{90} should be in the range of 6 to 17 to avoid that the blocks sink into the underground material or have the tendency to slide towards the ramp toe in case of high discharges. Lange (2007) showed that the maximum slope of block ramps of type B is approximately 6% for structured block clusters and 3% for unstructured blocks.

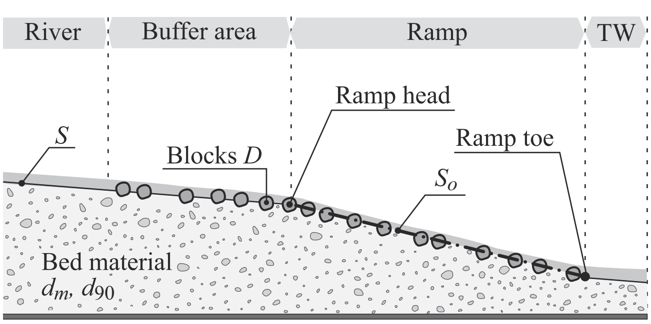

Figure 2. Scheme and notation of unstructured block ramps, where S = river slope, S_o = ramp slope, TW = tail water.

Whittaker and Jäggi (1986) performed experiments with block ramps of type A (with interlocked blocks as well as with dumped blocks, Fig. 1) with different block diameters D, bed material d_c, bed slopes S, and ramp length L_R. As one of their results they defined three different failure mechanisms for block ramps: 1) destabilization of single blocks, 2) entrainment and washout of the bed material below the blocks, and 3) scouring and failure of the ramp toe. In all three cases the failure of the block ramp is more or less an abrupt process.

In case of block ramps of type B hydraulic overload does not lead to an abrupt failure (Weichert, 2007), because the different block clusters are able to adjust themselves to a certain extent. The structure is less rigid compared to block ramps of type A, and sensitive elements such as ramp head or toe can be reinforced. To further improve the flexibility and the corresponding failure chain, Bezzola et al. (2005) and Janisch-Breuer (2007) performed experiments with unstructured block ramps where the concept of a buffer area upstream of the ramp has been developed (Fig. 2).

A certain section of the river upstream of the ramp head (approximately 1 to 2 times the river width) is covered with blocks of the same diameter and block density as on the ramp (Fig. 2). In case of hydraulic overload the buffer area allows adjustment and reduction of the ramp slope without an abrupt destruction of the complete structure as in the case of block ramps of type A.


Figure 3: Downstream view of an unstructured block ramp (Wyna River, Switzerland) under undulating flow conditions.

Aberle (2007) classified the flow on block ramps of type A in four typical categories depending on discharge and on tail water level. It is assumed that critical flow occurs on the ramp head (flow conditions change from subcritical to supercritical) and a hydraulic jump occurs at the ramp toe or, depending on the tail water level, somewhere on the ramp. However, unstructured block ramps of type B mostly lead to undulating flow conditions with Froude numbers close to one (Janisch and Tamagni, 2008) (Fig. 3).

3 HYDRAULIC DESIGN CRITERIA

In a first step the flow resistance for steep mountain streams is described, before we show special approaches to determine the flow resistance on different types of block ramps. In a second step existing stability criteria are given.

3.1 *Flow resistance*

In steep mountain rivers the hydraulic conditions are dominated by the interaction of steep slopes, large roughness elements, coarse bed material and the resulting morphological heterogeneities. Aberle & Smart (2003) stated that no standard flow resistance equation for mountain streams can be found in the literature. Most approaches are based on uniform flow condition and were developed for lowland rivers. In mountain rivers uniform flow conditions are rarely found and if so, only along short sections. Therefore, those approaches have to be applied with caution in case of alpine rivers and block ramps.

However, the flow resistance can be described based on boundary layer theory with the logarithmic law for rough walls in the following form:

$$\sqrt{\frac{8}{f}} = \frac{\bar{u}}{u_*} = \frac{1}{k}\ln\frac{h}{k_s} + B_r \quad (1)$$

where f = Darcy-Weisbach friction factor, $\bar{u}$ = mean flow velocity, u_* = shear velocity, k = von Karman constant, h = mean water depth, k_s = equivalent sand roughness, and B_r = constant. Many references can be found for the determination of the value of the von Karman constant k and of the constant B_r (i.a. Keulegan, 1938; Rouse, 1965; Dittrich & Koll, 1997). Typically values are $k = 0.4$ and $B_r = 6.6$.

Eq. (1) is valid for river reaches with constant slope S and constant bed material. However, in case of mountain streams with large roughness elements or unstructured block ramps, this assumption is not reasonable, except for very short sections. Therefore, Aberle (2000) proposed to use the standard deviation of the bed profile s instead of the characteristic grain diameter d_c to describe the bed roughness.

Based on a study of Scheuerlein (1968), approved by DWA (2009), the flow resistance for block ramps of type A with interlocked blocks can be determined with an extended version of Eq. (1):

$$\sqrt{\frac{8}{f}} = \frac{\bar{u}}{u_*} = 3.93\ln\left(\frac{1}{\sigma(0.425 + 2.025\Phi S)}\frac{h}{k}\right) \quad (2)$$

where $\sigma < 1$ = air content parameter, $\Phi = D\,N^{1/2}$ = packing factor, D = equivalent block diameter, N = number of blocks per m^2, and $k = D/3$ = mean roughness height. The application range of Eq. (2) is limited to supercritical aerated uniform flow and to bed slopes of $10\% < S < 67\%$.

For block ramps of type A with dumped blocks Rice et al. (1998) suggested the following relationship, approved by DWA (2009),

$$\sqrt{\frac{8}{f}} = \frac{\bar{u}}{\sqrt{ghS}} = 2.21\ln\frac{h}{d_{84}} + 6.00 \quad (3)$$

Eq. (3) was derived from model tests carried out on riprap-lined channels with bed slopes ranging from 2.8% to 33% using angular riprap with median diameters ranging from 52 to 278 mm.

According to Pagliara & Chiavaccini (2006) the flow resistance of ramps type B with structured or unstructured blocks can be determined with the following expression

$$\sqrt{\frac{8}{f}} = \frac{\bar{u}}{\sqrt{ghS}} = 3.5(1+\Gamma)^C S^{-0.17}\left(\frac{h}{d_{84}}\right)^{0.1} \quad (4)$$

where C = parameter describing the block material and the block arrangement (the values of C for random and row arrangement with rounded or crushed shaped block are given in Pagliara & Chiavaccini, 2006), and Γ = block placement density and is defined as

$$\Gamma = \frac{N_B \pi D^2}{4WL} \quad (5)$$

where N_B = number of blocks, D = block diameter, W = ramp width and L = ramp length. Eq. (4) shows that the flow resistance on a block ramp of type B additionally depends on the block density, on the block arrangement and on the blocks roughness. Pagliara & Chiavaccini (2006) showed that the influence of Froude number and relative submergence is negligible in the tested data range, with $0.8 < \mathsf{F} < 2.9$ and $0.6 < h/D < 2.6$.

Different studies were carried out to define the optimal value for the block placement density Γ_{opt}, to achieve maximal flow resistance. Schlichting (1936) found an optimum value of $\Gamma_{opt} = 0.4$ for spheres on a fixed bed; O'Loughlin & MacDonald (1964) determined $\Gamma_{opt} \approx 0.26$ for spheres, cubes and sand on a fixed bed; Dittrich & Hamman de Salazar (1993) investigated the relationship between the optimal block placement density, the flow resistance, the velocity and the slope, resulting in a diagram for Γ_{opt}.

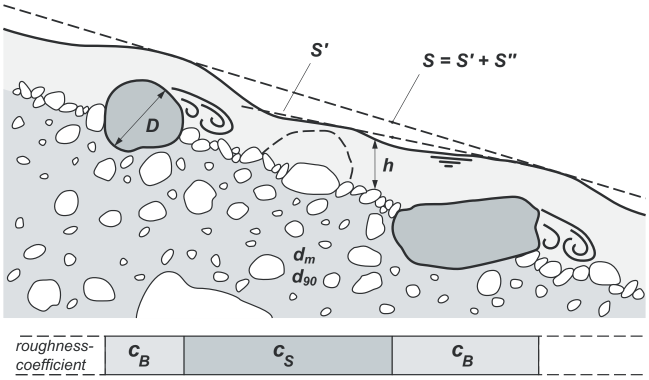

Figure 4. Definition used by Whittaker et al. (1988) to determine the flow resistance (Bezzola 2005, modified).

Another approach to determine the flow resistance for ramps of type B with unstructured blocks is proposed by Whittaker et al. (1988). They distinguish the resistance due to the grain friction of the bed material and additional form drag of macro roughness elements. The total flow resistance is given by the superposition of the two elements (model of composite roughness, see Fig. 4). With the Chézy coefficients

$$c_S = \frac{\overline{u}}{\sqrt{gR_h S'}} = 2.5 \ln \frac{12 R_h}{k_s} \tag{6}$$

for the flow resistance due to the bed material, where S' = slope of grain friction, k_s = equivalent sand roughness for the bed material; and

$$c_B = \frac{\overline{u}}{\sqrt{gR_h S''}} = 2.5 \ln \frac{12 R_h}{k_B} \tag{7}$$

for the flow resistance due to the macro roughness elements, where S'' = slope of form friction, $k_B = N_B \cdot D^3$ (17.8-0.47 h/D) = equivalent sand roughness for the macro roughness elements; the flow resistance can be calculated with

$$\frac{1}{c^2} = \frac{1}{c_S^2} + \frac{1}{c_B^2}\,. \tag{8}$$

Both the block diameter D and the number of blocks N_B are thus considered. The application range is limited to 0.1% < S < 5%, 0.5 < h/D < 4, and $N_B \cdot D^2$ < 0.15 per unit area. Whittaker et al. (1988) showed that the submergence level h/D has a major influence on the flow resistance.

The approaches given above to determine the flow resistance, flow velocities and water depths can be calculated iteratively by using one of the standard flow equations.

3.2 *Ramp stability*

To directly determine block diameters that meet the above calculated hydraulic conditions, DWA (2009) proposed the following equation for block ramps of type A with interlocked blocks:

$$u_{crit} = 1.2 \sqrt{2g\,(s-1) \cos\alpha\, D_B} \tag{9}$$

suggested by Hartung & Scheuerlein (1970), where u_{crit} = critical flow velocity, $s = \rho_s / \rho_w$ = ratio between sediment and water density, ρ_s = sediment density, ρ_w = water density, α = ramp inclination angle (in degree), and D_B = equivalent block diameter, which can be defined as

$$D_B = \sqrt[3]{\frac{6\, m_B}{\rho_s \pi}} \tag{10}$$

where m_B = block mass, if the block is simplified as a sphere, or as

$$D_B = 1.06\, D_{65} \tag{11}$$

according to Whittaker & Jäggi (1986).

Whittaker & Jäggi (1986) suggested the relationship

$$q_{crit} = \frac{0.257}{S^{7/6}} \sqrt{g\,(s-1)\, D_{65}^3} \tag{12}$$

for the determination of the stability of block ramps of type A with dumped blocks, where q_{crit} = critical specific discharge, S = ramp slope, and D_{65} = characteristic 65% block diameter. Eq. (12) was developed for ramp slopes steeper than 5%. Further researchers (i.e. Palt & Dittrich, 2002) suggest a modification of Eq. (12), mostly in the power coefficient of the ramp slope S and in the value of the numerical coefficient.

For ramps type B with structured blocks Aberle (2000) suggested

$$q_{crit} = 0.062\, S^{-1.11} \sqrt{g\,(s-1)\, D_B^3}\,, \tag{13}$$

which is of the same structure as Eq. (12), but has a lower value of the numerical coefficient and a slightly lower power coefficient of the ramp slope S. In Vogel (2003), Weichert (2006), and Weichert et al. (2009) modifications of Eq. (13) are found.

The stability of ramp type B with unstructured blocks is given by the equilibrium condition of all the forces exerted on a block. The details of this method and the description of all the forces which have to be considered can be found in Janisch et al. (2007) and in DWA (2009).

On the basis of the above mentioned Equations (9) to (13) and further suggestions from literature, the required block diameter D can be determined for the considered block ramp type and design conditions. It should be noted that all of the above mentioned approaches do not take into account the stabilizing or destabilizing effect of incoming bed load.

4 ECOLOGICAL DESIGN CRITERIA

The ecological functionality or ecological status of a block ramp is mainly determined by the two following criteria: 1) fish and other species can pass the block ramp (up- and downstream), 2) appropriate habitat conditions for certain species can be found on a block ramp.

Nature-oriented heterogeneous structures covering the complete river width (as in the case of unstructured block ramps) have many relevant benefits: They 1) provide a multitude of adequate migrant passages; 2) guarantee a heterogeneous bed structure leading to areas of low flow velocities, and 3) provide additional habitat conditions.

Several parameters regarding fish characteristics have to be considered by planning a block ramp. First of all the swim capacity of local species has to be known. One distinguishes between sustained, prolonged and burst swim velocity (DWA, 2009). A certain maximal swimming duration is related to a given swim velocity. By sustained swim velocity a fish can swim more than 200 minutes, by prolonged swim velocity up to a maximum of 200 minutes and by burst swim velocity only between 3 and 20 seconds. Table 1 summarizes maximal tolerable flow velocities v_{max} and maximal tolerable level differences Δh_{max} for typical Alpine regions and fish species.

Table 1. Maximal tolerable flow velocity and level difference for typical Alpine regions (Gebler, 2007)

	v_{max}	Δh_{max}
Trout	2.00 m/s	20.0 cm
Grayling	1.85 m/s	17.5 cm
Barbus	1.70 m/s	15.0 cm
Bream	1.40 m/s	10.0 cm

Other approximations for the different swim velocities, as well as details about maximal tolerable flow velocities and level differences for several fish species can also be found in DWA (2009).

It is important to note that none of the different migrant passages within a block ramp should exceed these conditions. Concerning migrant passages, it has to be specified that every fish species prefers a certain water depth. Thus, the local velocities in a migrant passage should be favorable for the different requirements at every water depth. Furthermore, the fish body dimensions have to be taken into account.

The design of an ecological sustainable structure has to account for the geometrical requirements of the biggest local fish species as well as the limiting swim capacity of the weaker local fish (DWA, 2009). On the basis of these boundary conditions given by the existing species, block ramps with suitable local conditions (i.e. flow velocity and water depth) can be designed. These boundary conditions are given for typical middle European conditions, e.g. in DVWK (1996), Gebler (2007), Peter & Müller (2007), and DWA (2009) (see also Tab.1).

Block ramps do not have to serve the same ecological conditions during the whole year (Gebler, 2007; Hunziker et al., 2008; DWA, 2009). It is admissible that during dry seasons (e.g. for discharges < Q_{30}, where Q_{30} = discharge, which is not exceed 30 days per year) and during flood events (e.g. for discharges > Q_{330}, where Q_{330} = discharge, which is not exceed 330 days per year) the ecological requirement do not have to be completely fulfilled. A low water channel can assure a minimal water depth during dry periods and make it passable also during low discharges.

During the design process of a block ramp, ecological aspects must not be neglected. The necessary requirements regarding maximal flow velocity, minimal water depth and certain geometrical dimensions have to be respected, in order to guarantee the environmental sustainability of the block ramp.

5 CURRENT PRACTICE AND FUTURE RESEARCH

The aim of this paper is to summarize existing design criteria and their limitations for block ramps, with respect to hydraulic and ecological aspects. The basis for today's block ramp design and especially for unstructured block ramps is basically summarized in the two mentioned manuals (Hunziker et al., 2008; DWA, 2009). Possibilities, restrictions and simplifications as well as ecological considerations given in these two manuals are discussed in the previous sections.

No universal approach describing the flow condition on a block ramp is given up to date. The variability of the roughness elements in longitudinal and transverse direction of a block ramp is difficult to parameterize and makes an exact description and quantification of the flow difficult. Furthermore, relating to the unstructured design, a hydraulic and a cost-effective optimum between the block placement density and the block diameter should be found taking into consideration the ecological requirements mentioned before.

Practical experience shows that block ramps can fail even if they have been properly designed and even under discharge conditions much below the design value. An important parameter is the quality of the construction procedure. According to Bezzola (2005) every ramp is stable as long as its weakest point is stable. Therefore, not only the block stability must be guaranteed, but every constructive detail must be accurately planned and realized. Ramp head, ramp toe, transition area between natural river bed and buffer area or block ramp, connection between block ramp and bank or bank protection are critical issues, which need particular attention.

In addition, the boundary conditions in the field rarely match the experimental conditions that are the basis for the existing design criteria. Fig. 5 shows an unstructured block ramp designed and built in 2009 in the Wyna River (Canton Aargau, Switzerland). In contrast to experimental conditions the "Wyna Ramp" is located in a river bend, leading to additional uncertainties regarding the design.

Figure 5. Ramp type B with unstructured blocks at the Wyna River (Canton Aargau, Switzerland) with a specific discharge q of about 0.16 m^2/s (view against flow direction). Source: Hunziker Zarn & Partner.

In order to further improve the understanding of hydraulic and ecological conditions in the case of unstructured block ramps further experiments are planned at VAW. The research project includes two tests phases. Firstly, the ramp behavior is studied related to the bed structures, which occur during different discharge conditions and under different bed load transport conditions. Secondly, the turbulence characteristics occurring on the ramp and between the blocks is studied using a fixed bed topography derived from the model tests in the first phase. The results are used to determine not only flow resistance but also to describe the ecological properties. Additional focus will be given on the boundary conditions linking the block ramp to the up- and downstream river reach.

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