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Piano Key Weir Research: State-of-the-Art and Future Challenges

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Abstract: *Piano Key Weirs (PKW) are non-linear weir structures, which were developed in the late 1990s. In the following years several structures were investigated in experimental as well as numerical models and were also built in prototypes, especially in France. Thereby, PKWs represent an improvement and further development of so called Labyrinth weir, but with an additional increase of discharge capacities and a reduced footprint. Two main PKW applications can be separated in research projects: (1) on top of dams (flood release structures) and (2) in-channel applications (replacement of regular weirs). The main difference between Labyrinth and Piano Key Weirs can be found in basic geometry components. While for Labyrinth Weirs the geometry follows a kind of accordion shape with vertical weir walls (velocity distribution close to the flow surface), the PKW design is more complex and includes sloped inlet and outlet keys, placed on a small footprint area. In this context, the general flow characteristics are also modified because the inlet and outlet keys can reach flow areas close to the river bed (for in-channel application). Hence, the velocity distribution differs majorly from those found in Labyrinth weirs—and with it resulting phenomena like scouring or sediment transport. The present paper summarizes and highlights current research investigations and state-of-the-art solutions for PKW designs and calculations—especially for in-channel applications. Based on this comprehensive literature review, future challenges for PKW research projects are specified. Topics like general flow characteristics, scale effects, downstream scouring, sediment transport, drift wood log jams, fish climb capability, or concrete abrasion will be discussed in detail to identify current and further research needs in small-scaled and large-scaled experimental and numerical models.*

Keywords: *Piano Key Weir, PKW, in-channel, state-of-the-art, future challenges, labyrinth weir.*

1. Introduction

Piano Key weirs—also known as PKWs—are non-linear hydraulic structures with an increased discharge capacity compared to regular weirs. PKWs represent a further development of so called Labyrinth weirs with the major benefit of a much smaller footprint. Starting with Blanc and Lempérière (2001) and Lempérière and Ouamane (2003), several PKW geometries were investigated comprehensively in a handful of scientific laboratories all over the world. Large water research laboratories, such as those at Utah State University, University of Liège, EPFL, and German Federal Waterways Engineering and Research Institute; small sections, such as Luebeck University of Applied Sciences; and practitioners like EDF France, build and analyze PKW units for basic research investigations or practical case studies.

Generally, a PKW consists of inlet and outlet keys with a defined upstream and downstream overhang length and a weir foot (Fig. 1). Pralong et al. (2011) give a general notation for PKW parameters (Table 1). PKW geometries can be classified into Type A, Type B, and Type C, where Type A is characterized by symmetric overhang lengths and Type B has an overhang length only in upstream direction (into the channel/reservoir). Type C is the opposite of Type B. Ribeiro et al. (2012) defines primary (P and W) and secondary ($W_iW_o^{-1}$ and $P_iP_o^{-1}$) parameters for PKW analysis. The PKW efficiency can be calculated according to Poleni and Du Buat, although two points of view exist (Pralong et al. 2011; Oertel and Bremer 2016): (1) centerline crest length L and (2) total weir width W. Using the total centerline crest length, the Du Buat approach can be written as:

$$Q = \frac{2}{3} C_d L (2g)^{0.5} H_T^{1.5} \tag{1}$$

where Q = total discharge, C_d = discharge coefficient, L = total centerline crest length, g = gravitational acceleration, H_T = upstream energy head including the flow depth h_T, and depth averaged velocity head $v_T^2(2g)^{-1}$. Since this approach does not allow an adequate comparison of PKW efficiencies, the total weir width W can be used for efficiency statements (Bremer and Oertel 2017):

$$Q = \frac{2}{3} C_{dw} W (2g)^{0.5} H_T^{1.5} \tag{2}$$

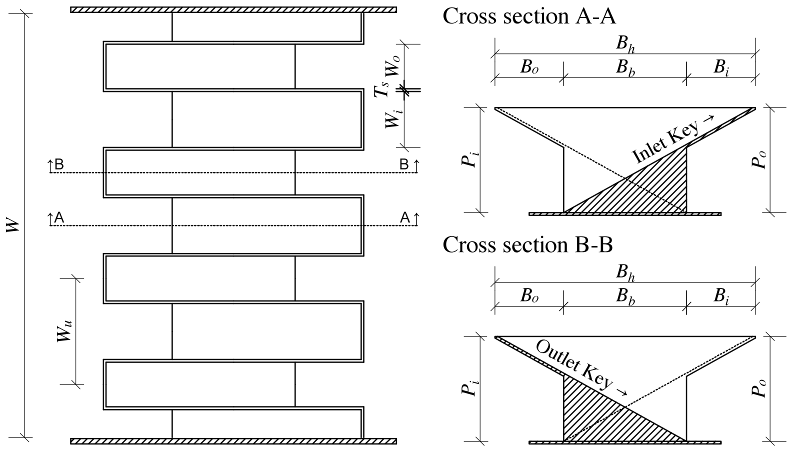

Figure 1. Main geometrical PKW parameters, left: plan view, right: sectional view (Oertel and Bremer 2016).

Table 1. Main geometrical PKW parameters (according to Pralong et al. 2011, Oertel and Bremer 2016).

Parameter	Specification
P_i	upstream weir height
P_o	downstream weir height
W_i	inlet key width
W_o	outlet key width
N_u	No. of PKW units
B_h	Sidewall overflowing crest length measured from the outlet key crest axis to the inlet key crest axis
B_i	downstream overhang length
B_o	upstream overhang length
B_b	weir foot length
T_s	wall thickness
W_u	PKW unit width, $W_u = W_i + W_o + 2T_s$
W	total weir width, $W = N_u W_u$
L_u	crest centerline length of PKW unit, $L_u = W_u + 2B_h - 2T_s$
L	total crest centerline length, $L = N_u L_u$

2. Statistical Literature Review

2.1. Basic Research Statistics

During the last two decades, several PKW research projects were arranged to identify general flow characteristics, discharge capacities, efficiency increases, flow patterns, and many more. Within this chapter, a comprehensive literature review will be presented, and statistical findings will be given for available PKW publications. Therefore, 135 PKW papers in total, which were published prior to November 2nd 2017, are analyzed.

Fig. 2a shows the type of publication concerning the chosen publication form. It can be found that only a handful of published papers are presented in international journals (see references), while a huge number has been prepared for conferences and workshop proceedings—especially for the International Workshop on Labyrinth and Piano Key Weirs in 2011 (Liège), 2014 (Paris), and 2017 (Vietnam). Approximately 61 % of these publications deal with basic research topics, while 28 % address project-related research studies (Fig. 2b). 11 % of the investigated research studies discuss both basic and project research studies.

The literature separated various PKW types and identified specific differences for in-channel and top-of-dam designs. Fig. 2c summarizes the investigated PKW types and shows an almost balanced research quantity for in-channel (37 %) and top-of-dam (46 %) studies. 17 % of the research was performed on other PKW types, like circular PKWs.

An important question concerning the chosen model types can be answered with Fig. 2d. It can be shown that 95 publications in total are based on physical or numerical models. With 62 %, the physical model is the most frequently used type of model, and numerical models comes along with 16 %. Within these quantities, combined models (hybrid models) are included with 8 %. The remaining 22 % use other methods, such as analytical approaches or theoretical considerations.

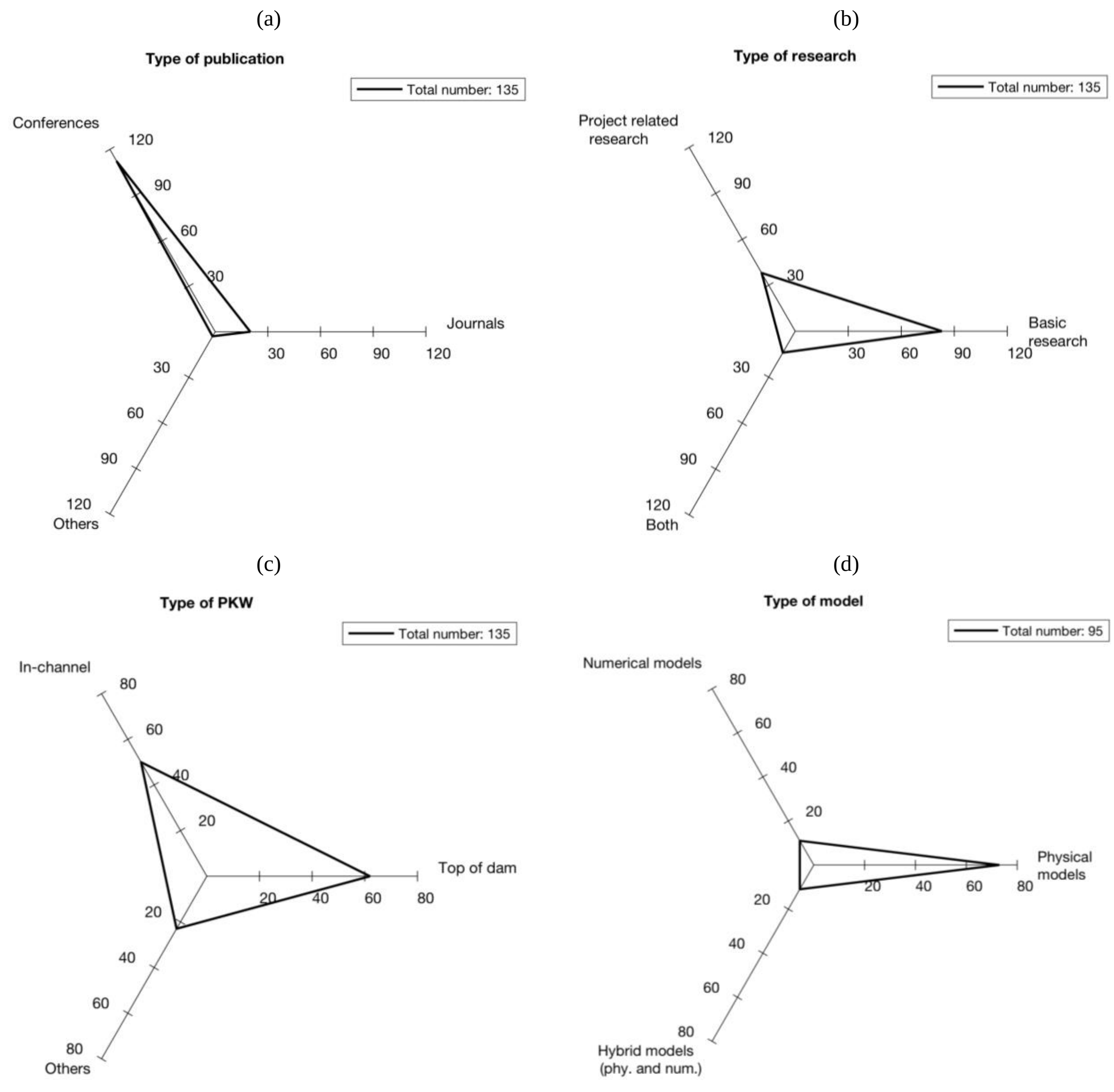

Figure 2. Basic PKW research statistics, (a) type of publication, (b) type of research, (c) type of PKW, (d) type of model.

2.2. Physical Model Statistics

Taking all 84 research papers dealing with physical models into account, a statistical analysis concerning chosen model scales and flume geometries can be given. Fig. 3a shows both model scales and flume geometries. Only 36 papers give detailed information about the chosen geometrical boundary conditions. Unfortunately, more than 50 % of the investigated papers do not include adequate details on the physical models. A statistical analysis of the presented 36 papers lead to the result that approximately 53 % of the physical models were investigated in scales between 1:50 and 1:10. Only a few models were investigated in scales smaller than 1:50. But 14 % of the models were built in larger scales than 1:5 (up to 1:1, prototype). Comparing these results with the total flume lengths L_F and flume widths W_F, it can be mentioned that the size of the laboratories is limited and consequently the ratio between the model size and total investigation area is being influenced. Typically, flume lengths larger than 7.0 m were chosen with comparable flume width ratios $L_F W_F = 10$.

The investigated total head ratios $H_T P^{-1}$ can be classified into minimum and maximum values, as seen in Fig. 3b. Most of the investigated model runs deal with minimum total head ratios between 0.05 to 0.10 and maximum total head ratios of 0.5 to 1.0. As seen in Fig. 4, especially for low heads $H_T P^{-1} < 0.1$, a characteristic increase and following decrease with a peak in the calculated discharge coefficients can be observed. To identify this peak precisely, it is essential to investigate small total heads with small discharge increments. On the contrary, this discharge coefficient area is of low interest for practical applications and is influenced by scale effects in small scale physical models. High heads $H_T P^{-1} > 0.4$ are of major interest for flood events and resulting upstream water levels. To analyze discharge coefficients in this area, smaller models can be used or large discharge capacities in the hydraulic laboratories are necessary. Fig. 3b shows a remarkable number of physical models analyzing $0.5 < H_T P^{-1} > 1.5$.

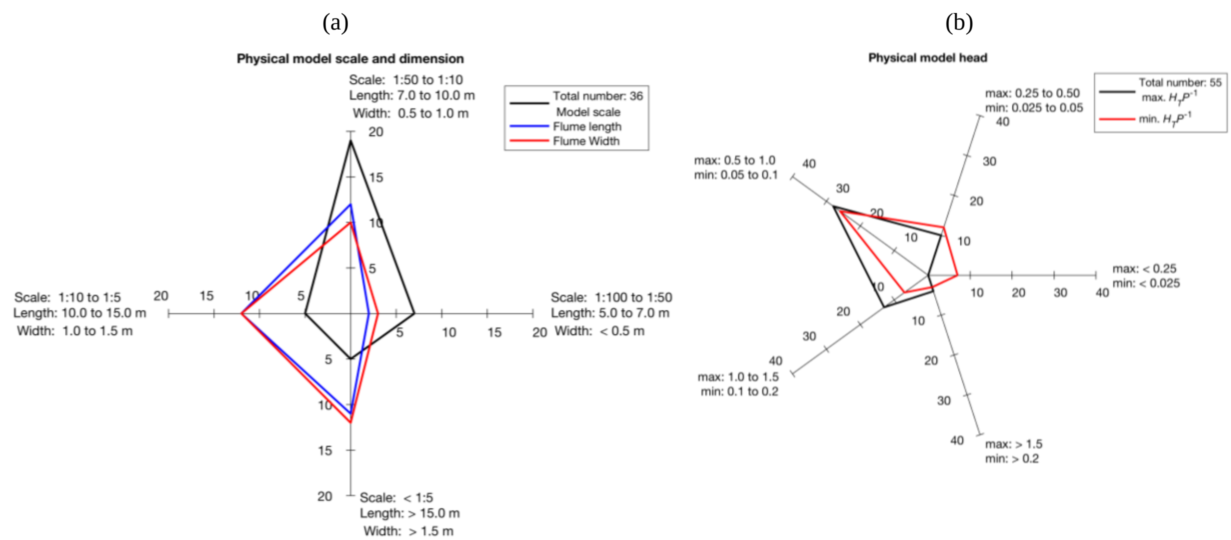

Figure 3. Physical model statistics, (a) model scale and dimension, (b) min. and max. total head ratio ($H_T P^{-1}$).

2.3. Research Topic Statistics

The investigated 135 papers were analyzed concerning the specific topic of research. Results are presented in Fig. 5. It can be found that, in total, 265 investigation topics were counted. Consequently, several papers deal with more than one of the listed topics (e.g., discharge coefficients and design guidelines are often connected). For statistical analysis research topics were alphabetically classified into (1) aeration, (2) analytical approaches, (3) cost analysis, (4) design guidelines, (5) discharge coefficients, (6) drift wood log jam, (7) energy dissipation, (8) general flow characteristics, (9) literature review, (10) others, (11) scale effects, (12) scouring and sediment transport, (13) submerged flow, (14) turbulence analysis, and (15) velocity distributions.

Following, some additional information will be given to clarify these various classifications. Publications dealing with cost analysis are usually focusing on project studies, where planned structures were investigated concerning resulting

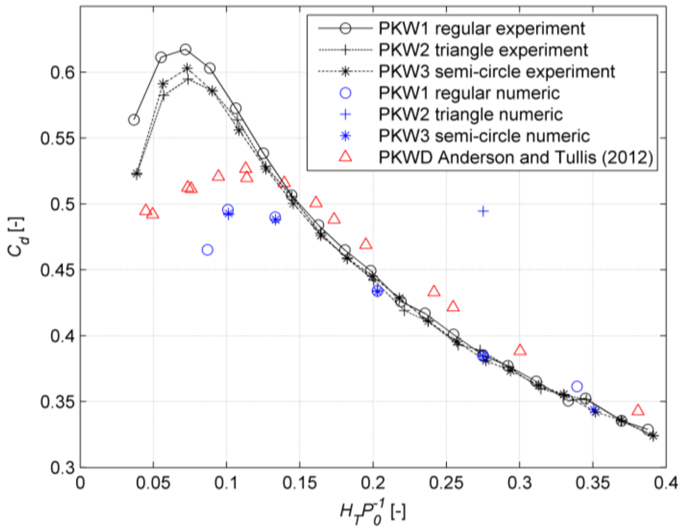

Figure 4. Exemplary discharge coefficients from scaled PKWD model (Oertel 2015).

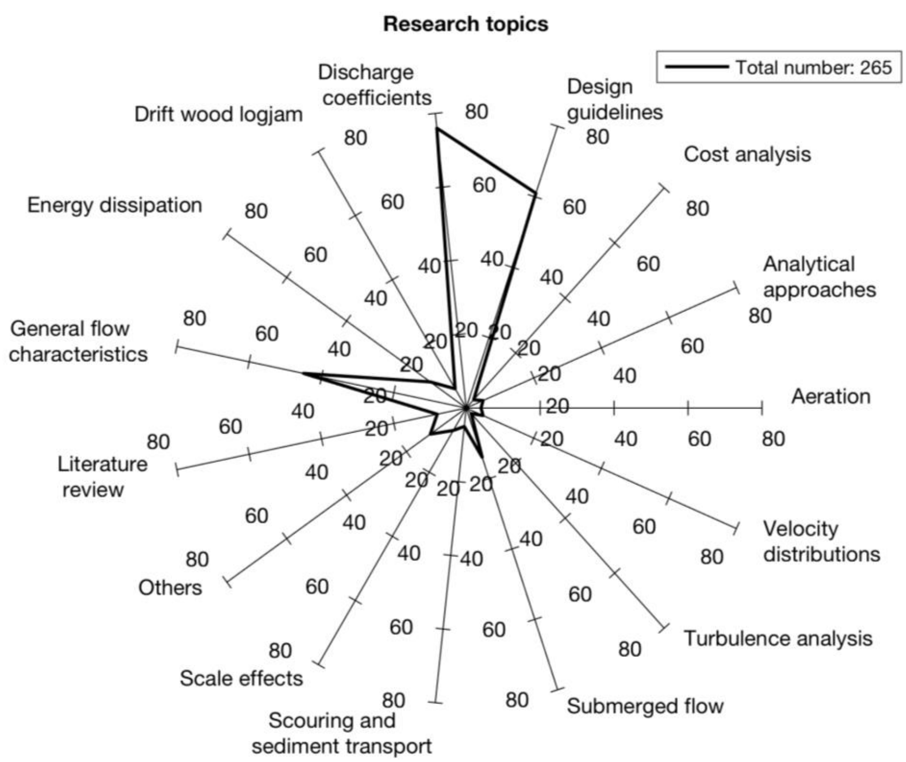

Figure 5. PKW research topics.

construction costs—but only a few papers with this topic exist. Numerous studies can be found with detailed developments of design guidelines. Thereby, discharge coefficients were also analyzed in a remarkable quantity of publications. General flow characteristics summarizes research topics like flow description, flow depth measurements, and more, which are not classified and counted in one of the other presented topics. Since PKWs were investigated predominantly within scaled experimental models, only a surprisingly small amount of investigations dealt with scale effects and their consequences on laboratory result analysis. Energy dissipation processes were analyzed for top-of-dam applications, where energy will be dissipated on a connected spillway or chute. Scouring and sediment transport is of major interest for hydraulic structures—but this topic has not been extensively considered within publications to date. A submerged flow is relevant for high discharge events in river systems and consequently for in-channel PKW applications. Approximately 30 % of the total number of in-channel investigations also observe downstream submergence. Summarizing, Fig. 5 clearly states that in comparison to other hydraulic structure research disciplines (e.g. stepped spillways), the PKW topic is young and a lot of investigation programs are still necessary to complement and enlarge the scientific knowledge for this kind of hydraulic structure.

3. Future Challenges

Although a lot of experimental and numerical research investigations are available in the literature, the PKW topic is relatively young, and, consequently, unanswered questions exist for various areas of interest, as mentioned before. Due to this existing lack of knowledge, exemplary ideas and needs for future research studies and challenges are given subsequently:

(1) General flow characteristics and laboratory techniques:

- Influence of various geometrical parameters; e.g. weir height, width, inlet and outlet geometry, wall thickness.
- Especially for small PKW heights in river systems, material like steel might be used for PKW design. Hence, small wall thicknesses can be achieved, which have not been investigated in detail yet.
- At flood release structures, the energy will be dissipated on additional structures like downstream chutes or stepped spillways. For in-channel PKWs the energy dissipation processes on the PKW itself are not well analyzed.
- Scale effects.

(2) Upstream flow characteristics:

- As mentioned before, nowadays PKWs are not frequently used for in-channel applications (in Germany). Questions concerning drift wood log jams or ice are the focus of interest when replacing regular weirs with PKWs.
- Sediment transport is important for river system management. Hence, transport processes due to a changed velocity profile upstream the PKW must be analyzed.
- Detailed three-dimensional flow description (velocity distributions) within the inlet and outlet keys.

(3) Fluid structure interaction concerning material abrasion and erosion:

- Constructed PKWs are generally young (less than 10 years) compared to regular weirs. Consequently, knowledge of abrasion processes due to material/sediment transport is limited. It is necessary to analyze possible transport processes along the structure since the velocity profiles may allow an intensive sediment transport in contrast to regular weirs, where the velocity profile close to the river bed is low and material deposition takes place. PKWs are often made of reinforced concrete and the fluid structure interaction process has not been studied yet.
- Scouring downstream for varying 3D velocity profiles in the stilling basin.

(4) Further geometrical developments:

- Combinations of PKWs with in-structure fish steps for upstream and downstream fish migration are not analyzed yet. PKW units will transform rivers into Heavily Modified Water Bodies, like regular weirs. Within the EU-WFD (2000), fish migration (biological components) is of major priority next to other aspects, such as hydro-morphological and chemical components. Including a fish step within a PKW key might be of major interest, especially for PKWs with smaller heights and made of steel.

(5) Numerical 3D CFD simulations:

- Only a few investigations are available in the literature, so a lack of knowledge still exists. Numerical CFD models must be calibrated via laboratory or prototype data. Numerical boundary conditions, like model lengths, inflow characteristics, cell sizes, and turbulence models, among others, are not defined adequately for PKW studies.

4. Summary and Conclusion

By analyzing PKW research studies, it could be found that only a few journal publications exist, and most of the published papers were placed at conference proceedings. In-channel and top-of-dam application studies have a comparable quantity, while most of the studies were carried out in physical model test. Physical models were predominantly scaled between 1:50 to 1:10, but prototype studies are also available.

By means of a comprehensive statistical literature review, main PKW research areas were identified. Consequently, research deficits and further investigation needs were mentioned and listed as exemplary future challenges.

Concluding, PKW research topics are relatively new compared to other hydraulic investigations. Hence, a lot of unanswered questions concerning general hydraulic phenomena, as well as special structure designs, etc., still exist. It can be expected that additional PKW research topics will be developed during the next decade(s), and several questions will be answered by means of physical and numerical models, as well as prototype measurements.

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