CHAPTER 1 INTRODUCTION

Water is critical to the survival of all living organisms. Of all the water on Earth, just 2.5% is fresh water. Fresh water can be found in glaciers, reservoirs, lakes, streams, ponds, rivers, wetlands and groundwater. This limited resource covers less than 1% of the world's total surface area yet houses 10% of all animals and up to 40% of all fish species. Freshwater is the fundamental constituent of all life forms, and the river is an essential source of freshwater in the earth.

The substantial population growth has initiated a water stress scenario (Shukla et al. 2013). The conflict between Israel and its Arab neighbors over control of water sources in the Jordan River drainage basin back in 1967, the increasing dispute over Nile Basin, Afghanistan and Iran Water Dispute, Long time Tensions in the Euphrates-Tigris basin, recent Political Tension between India and Pakistan regarding the Indus Treaty, Cauvery Water Dispute in India within states stand testimony to the increasing water conflicts as the rivers are the main contributors of freshwater among the surface sources along with providing groundwater water requirements. The study of optimal allocation of water resources from river basins and the river water quality, as such, is necessary (Arora and Keshari 2020; Keshari 2000). The ground water, which is also the source of drinking water and other industrial uses, also requires quality monitoring for avoiding health hazards(Bhattacharya et al. 2008; Keshari 2003; Ramanathan et al. 2009). This use of a finite Resource has led Researchers around the world to move towards sustainable and optimum use of Water. Hydraulic structures are frequently used for water resources development and management. Dams, barrages, weirs, head and cross regulators are some significant structures, and they are applied to store and regulate the surface water of the river. The flow domain in the vicinity of these hydraulic structures consists of spatial and temporal variations of velocity.

India is a monsoon country with rainfall not falling throughout the year but concentrated in 3-4 months. This implies India gets all of its freshwater resources in around 3-4 months.

The unbalanced distribution of water at different scales vis-à-vis time, space, and quality (a typical feature of the Indian water resource system) renders a higher degree of difficulty for flood management and the utilization of water resources (Gaur et al. 2008; Gupta and Deshpande 2004; Kumar et al. 2005; Samal and Gedam 2013; Sen 2010). This demands an obligation for the man-made redistribution of water by undertaking valuable engineering procedures to get water to a particular place and in a specified amount along with a fixed moment in time. The intactness of such engineering procedures forms a split part of the cost-cutting measure, which is termed water utilization. This leads to a greater responsibility on the water resource professionals to better manage this finite water source so that its sustainable use can be availed all around the year. The timely and appropriate usage of water resources is one of the fundamental assistances produced to human society by the water resource engineer.

1.1 Transverse Hydraulic Structures

Civil engineering structures accepted for dealing with explicit water utilization responsibilities are called hydraulic structures. The applied science concerned with hydraulic structure's common hypothesis, design and drawing, development and functioning is termed hydraulic engineering. Hydraulic structures are the critical infrastructures that are used for water resources management. The primary job of hydraulic engineers is to homologize the natural regime of the water body (e.g., rivers, seas, lakes, underground-waters, etc.) to intend economic and worthwhile water utilization (Pramanik et al. 2010; Pramanik et al. 2011). The secondary job of hydraulic engineers is to establish artificial reservoirs and watercourses when there is a deficit of natural resources. Two types of hydraulic structures are typically built to accomplish the aforesaid jobs: general hydraulic structures and special hydraulic structures. The general hydraulic structures are common to all water utilization branches, while special hydraulic structures serve to accomplish the uses to classify water utilization branches (Novak 2005; Novak et al. 2010; Novak et al. 2007). General hydraulic structures can be split up into three main types: water-retaining, water conveying and intake structures. Special structures can be classified as structures for hydropower, water transportations, water supply, irrigation, drainage systems etc.

Hydraulic structures are defined as transverse hydraulic structures placed across the open channel, with their applications dating back to the 18^{th} century or earlier. Hydraulic structures can be illustrated as engineering components used in water resources development, allowing for upgraded or altered flow features in contrast with a natural flow. Hydraulic structures can be applied to deflect, interrupt, or completely stop the natural flow. They either enhance the flow passage by diminishing resistance or are embedded in water bodies to repel, disseminate, or contract the streamflow.

With the progress of science, technology and understanding of its utility, transverse hydraulic structure has been modified from time to time. Alterations in their plan shape (straight, diagonal, V, W, labyrinth, PKW etc.) or sectional shape (triangular, rectangular, trapezoidal etc.) have been done from time to time. Adjustments of the shapes alter the physics of flow behind the transverse structures. Unique hydraulic structure incurs unique flow mechanism (first, second or higher-order) in the vicinity of structure (either upstream, downstream or around). The development of different hydraulic property measuring instruments facilitated the exploration of the features of the flow mechanism in detail.

Dams are important water retaining structures used very frequently across the globe. Weirs are also the barrier in the channel to divert the flow to the desired location. It is generally small in size compared to large conventional dams. There are 4862 completed large dams, and 312 large dams are under construction in India. India lies in the third position after China and the USA with respect to the number of dams. Irrespective of dimension and nature, structures exhibit great complexity in their hydraulic response.

Dams are the most former and elemental type of civil engineering hydraulic structures. All great cultures have been discovered with the construction of dams and reservoirs appropriate to their demands to meet drinking and irrigation demands originating through the evolution and elaboration of engineered farming (Novak et al. 2007; Suryawanshi et al. 2012). Dams fall in "installations containing dangerous forces" under International humanitarian law because of their tremendous impact as well as possible destruction caused by their failure on civilian life and the environment. The risk results from imperfections of man’s work and in the design and construction of dams. Protection of the people from the consequences of dam failures has taken on increasing importance as populations have concentrated in limited and vulnerable areas. Performance of the dam under probable maximum flood (PMF) conditions is an essential aspect of dam safety evaluation. The dam should serve its dual purpose of impounding smaller floodwaters for judicious use later while safely passing the larger floods downstream without overtopping the dam.

Flood studies are carried out to determine the reservoir storage needed to accommodate a given flood, freeboard allowance needed during an inflow design flood, and spillway design needed to pass excess floodwaters downstream.

The most crucial variable that represents the hydrological safety of the dam is the maximum water level reached in the reservoir (Bianucci et al. 2013; Gabriel-Martin et al. 2017; Micovic et al. 2016). The initial reservoir level is a significant parameter for estimating dam overtopping probability in the rainy season (Kwon and Moon 2006). Gate functionality has also to be considered as gates may not open during floods when needed because of human, mechanical or electrical failure(Lewin et al. 2003; Micovic et al. 2016; Patev and Putcha 2005). Reservoir dams are generally encountered with two primary issues, the first is flood control, and the second is storage capacity loss due to high sedimentation rate (Sarma et al. 2015).

Most of the dams are equipped with spillways/weirs. The function of the Spillway is to pass flood water, and particularly the design flood, safely downstream when the manmade reservoir is spilling over (Savage and Johnson 2001; Sorensen 1985). Spillways are mainly classified according to their controlling nature. Spillway constitutes a fraction of the total dam cost. The available information indicates a significant variation, ranging from 4% (unlined rock spillways) to 22% (spillways for earth and rock-fill dams). There is a large amount of investment for the spillways in terms of cost.

Spillways have two main components: the controlling spill-weir and the spillway channel, the function of the second being to carry flood flows safely downstream of the dam. The second may comprise a stilling basin or other energy-dissipating devices. Spillways are generally uncontrolled, i.e., they serve automatically as the water level goes over NWL. They may be operated by use of gates or without them. The spillway capacity safely reconciles the maximum design flood, the spill-weir level prescribing the maximum holding level of the dam, i.e., the maximum water level (Johnson 1936).

Studies of dam failures worldwide and their causes suggest that the inadequacy of spillways results in about 23% of Dam failures. Inadequate Spillway also leads to overtopping of Hydraulic structures, leading to erosion, seepage problems, and even failure. Inadequate Spillway leads to high pore water pressure within the dam body besides contributing to breach in the lateral cross-section.

Studies of dam failures worldwide and their causes as in percentage distribution of dam breaks have been presented below with causes of failure (Table 1.1).

Table 1. 1 Reasons of Dam Failure

Failure Reasons	Percentage
Problem in Foundation	40%
Inadequacy of spillway	23%
Poor Construction practices	12%
Settlement of foundation(uneven)	10%
Pore Water Pressure	5%
War	3%
Defective Materials	2%
Slips in Embankment	2%
In correct Operations	2%
Natural causes such as Earthquakes	1%

Besides, these notable Dam failures have occurred globally mainly due to massive floods overtopping like the moraine dam breach (Begam et al. 2018) and insufficient spillway capacity. With increasing floods and avoiding the danger of overtopping, many spillways require replacement or an increase in their discharge capacity.

Table 1.2 gives a brief history of notable Dam failures in India. Subsequently, Research has been carried out extensively to design a spillway to pass maximum flood waters through the minimum head. Free-flow spillways are simpler and reduce the risk of not opening during high floods, and are safer than gated ones.

Table 1. 2 Notable Dam Failures in India

Dam	Dam Type	Reason
Kaddam Project Dam, Andhra Pradesh	Composite	Inadequate Spillway capacity. This was the first dam failure noted due to Inadequate spillway capacity
Kaila Dam Gujarat	Earthfill	Insufficient Spillway and weak foundation
Kodaganar Dam, Tamil Nadu	Earthfill	Insufficient Spillway led to overtopping and later also hit by an earthquake.
Machhu II Dam, Gujarat	Composite	Insufficient Spillway leading to overtopping and a loss of 1800 lives.
Panshet Dam, Ambi, Maharashtra	Under Construction	The failure resulted due to inadequate provision of the outlet facility during an emergency. This resulted in the collapse of the structure above the outlets.
Khadakwasla Dam, Mutha Maharashtra	Masonry Gravity Dam	Overtopping due to Flood
Tigra Dam, Madhya Pradesh	Masonry Gravity Dam	Overtopping and Sliding

Still, they have very low specific flow because of their traditional shapes, which require high spilling nappe depths and thus massive losses in storage (100 x 109m^3 worldwide) (Lempérière and Ouamane 2003).

The issue of submergence is directly associated with the placement of any transverse hydraulic structure in the open channel. Placement of transverse hydraulic structure across the open channel alters flow conditions in the upstream and downstream. There is submergence upstream of the hydraulic structure, and it must be considered before the design. This paper presents a review of a new type of weir installation called Piano Key Weir (PKW), which is becoming popular around the world for its higher spillway capacity both for existing and new dam spillway installations. This paper reviews the geometry along with structural integrity, discharging capacity, economic aspects, aeration requirements, sediment transport and erosion aspects of Piano Key Weir (PKW) compared with other traditional spillway structures and alternatives from Literature. The solution to increasing the dam's safety is affected by physical and economic conditions as well as by local tradition and limited engineering knowledge. Adding spillway capacity in the original design involves loss of storage or construction of gates, which may not always be possible or economical. Increasing reservoir levels is another option to reduce the cost of adding discharge capacity per centimeter. An increase in reservoir storage can be accomplished by improving the embankment crest or adding fuse plugs that are limited to only new constructions, or adding a device such as Piano Key Weir.

The comparison with other alternatives shows PKW to be excellent for dam risk mitigation owing to its high spillway capabilities and economy, along with its use in both existing and new hydraulic structures.

Piano key weir in this regard provides an excellent alternative for dam risk mitigation.

Firstly since PKW are free-flow weirs, they reduce the risk of non-opening of gates during floods. Secondly, PKW has higher discharge intensity and even allows recovery of the global storage volume (Lempérière and Ouamane 2003).

PKW has a higher discharge capacity, which can safely pass the excess floodwater downstream with a lesser upstream level than for a gated dam when the reservoir is lower than the natural level of an extreme flood (Lempérière et al. 2011).

The scope of the study is very high to standardize the features of the Piano Key Weir because it is a relatively new hydraulic structure. In general, any weir has a specific head discharge relationship. Estimation of coefficient of discharge facilitates us to calculate the discharge passing through the weir via head measurement. The complexity of the relationship is increased with the types of hydraulic structures used for the discharge measurement and control. Since several structural parameters are involved with Piano Key Weir, the study of the head discharge relationship over Piano Key Weir has gained importance.

1.2 Earlier Research

The process of understanding nature relies on the experimental methods, observations and the fundamental principles of the relevant field. With advances in computing, numerical methods emerged, but they too have to be verified and validated with the experimental results. The results of the numerical methods depend on developing the correct mathematical model and providing proper boundary conditions for the same.

Hydraulic processes in nature are quite arbitrary, and thus the improbability because of this variability may be aptly quantified employing experimental and numerical study. Hydraulic structures obstruct the natural fluid flow and thus encounter or produce turbulent flow fields (Bennett and Best 1995; Grass 1971). The flow, as such, are generally unsteady flows and often display high turbulence. Research and development near hydraulic structures (especially in the vicinity of the dam, barrage, bridge pier, rectangular weir, and labyrinth weir) have been among the leading areas for water scientists and practitioners (Bray et al. 2016; Chadwick et al. 2013; Tanchev 2014). Mechanism of flow and momentum transport (useful for sediment transport) near the bridge piers is a significant research area for hydraulic engineers (Barbetta et al. 2015; Najafzadeh et al. 2013). Any structure placed in the river or open channel creates a distinct disturbance to natural water flow(Jamieson et al. 2011). As the Piano Key Weir is a relatively new transverse hydraulic structure, any experimental study and numerical analysis will improve the usability of the structure (Bieri et al. 2009; Chi Hien et al. 2006). Detail literature review of the Piano Key Weir has been given in Chapter 2.

1.3 Research Needs

Significant research has been carried out to establish the head discharge relationship for Piano Key Weir (Anderson 2011; Erpicum et al. 2012; Kabiri-Samani and Javaheri 2012; Kumar et al. 2019; Leite Ribeiro et al. 2009; Machiels et al. 2009; Machiels et al. 2010; Ribeiro et al. 2012; Tiwari and Sharma 2017a). Comparison of different planforms of PKW warrants attention to decide on the hydraulically superior plan form. In the present research, different plan forms of PKW are compared for their head discharge, self-cleaning and partial outlet submergence study, both experimentally and numerically, in a constant channel width with the same developed length.

1.4 Objectives of the Study

1. A review of the hydraulic, economic, sediment passage, structural integrity and aeration advantages of Piano Key Weir compared to its counterparts from Literature.

2. Numerical study of the experimental results from the Literature to investigate the effectiveness of CFD studies in simulating the flow over Piano Key Weir. Also,

study the hydraulic advantage of Piano Key Weir compared to the rectangular weir in an open channel.

3. Investigate and compare the relative hydraulic superiority between rectangular and trapezoidal Piano Key Weir of varying angles.

4. Investigate and compare the sediment profile upstream of rectangular and trapezoidal Piano Key Weir of varying angles and study the sediment passage over these weirs. Study of vertical velocity component upstream of RPKW and TPKW and variations at the critical points identified in the experimental study and identifying regions of maximum scour.

5. Investigate the effect of partial to total submergence of outlets of PKW of different plan shapes on its discharge-head relationship.

1.5 Experimental Setup and Data Collection

Experiments have been the basis of science all along the course of civilization. Richard P. Feynman, in his beautiful lecture on the rules of scientific methods, has said and quoted, "It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with the experiment, it's wrong."

Experimental methods are generally based on three steps: experimental design, data collection and rectification, and data analysis. The smaller flume (F1) had 0.4 m width and the second flume (F2) had 0.984m width (relatively wider). Both the flumes are used to determine the percentage reduction of head over the crest of Piano Key Weir with respect to the rectangular weir. Both the flumes were used for discharge head variation study to identify the basic usability of Piano Key Weir. The smaller flume (F1) was used in addition to studying the sediment transport mechanism upstream of PKW. Besides the experimental approach numerical study has been carried out for determining the head discharge relationship of PKW and TPKW. The numerical study has been validated with the experimental data, and further study of vertical velocity components has been carried out using the validated numerical study. The larger flume (F2) was also used to determine the effectiveness of PKW under partial to total downstream outlet submergence on the head over PKW. The detailed experimental components and setups have been presented in each chapter.

1.6 Structural Conditions

PKW-A types have been taken in the study, which varies in their plan geometry. Four structural Piano Key Weir A (Rectangular plan Trapezoidal 6 degree, Trapezoidal 9 degree and Trapezoidal 13 degree) have been taken under consideration for this study. Specific details and features of the condition have been discussed in each chapter.

1.7 Instruments

An Instrument is an essential experimental component in hydraulic engineering study. Some of the instruments used in the study are described below:

Point Gauge

The measurement of spatial position is required during this study. This can be carried out using a manually adjusted hook, and a reading is taken from the vertical movement using a scale. The complete setup of hook and scale is known as Point Gauge. A Vernier scale on a point gauge has a least count of 0.1 mm.

Flume

Flume is an essential part of open channel flow experiments. As mentioned above, two different configuration flumes have been used for experimental purposes. Flume 1 (width = 0.4 m) is designated as F1 and flume 2 as F2 (width = 0.984 m). Discharges of the flume have been measured with the rectangular weir in the civil department laboratory at IIT (BHU), Varanasi. Measurement of water head has been carried out using a point gauge (equipped with a Vernier scale).

1.8 Limitations and Scope for Future Work

The experimental study and their analysis in this work are limited mainly to the upstream of Piano Key Weir. The principal driving force of this research work is to establish the hydraulic advantages among different plan forms of PKW and to study the head–discharge as well as sediment passage over these plan forms. The study of head and discharge over Piano Key weir is only limited to the lowest head and the geometry under experimentation. Further, the study is limited to the extent of the geometric parameters and the range of discharge variations used in the study.

1.9 Organisation of Thesis

The organization of this study is specified by The Indian Institute of Technology (BHU), Varanasi, India manual for Ph.D. ordinances. It includes a first chapter, "Introduction," briefly describing the relevance of this research and objectives. The second chapter, "Literature Review," concisely summarizes the hydraulic advantages of PKW while also focussing on the economy, structural integrity, sediment carrying capacity, standard aeration requirements and shape optimization. Several discharges and corresponding average head over PKW crest and linear weir have been measured through the experimental setup in Chapters 5 & 6. Here, the average head over crest means the water head from PKW crest level over multiple points has been taken and averaged out for every discharge.

The upstream of the flume was filled with granular sand from river Ganga to study the sediment profile upstream of RPKW and TPKW6. The experimental setup has been described in Chapter 5. Average head over PKW has been compared with rectangular weir heads to quantify head reduction with respect to the rectangular weir. Rectangular and Trapezoidal plan forms of PKW have been fixed at the same place in the channel flume to get a comprehensive overview of their discharge capabilities.

Rendering the tail gate partially closed ensured the outlets of PKWs were submerged partially to fully. The head over the crest of PKW was studied in this condition to detect any changes due to partial to complete submergence of outlets. The experimental setup has been described in Chapter 6.

The chapters are organized in the following way:

Chapter-1 This chapter presents an introduction to Transverse Hydraulic Structures. It further focuses on the research needs and outlines the study's objectives and salient features of the present work. The chapter further outlines the organization of this Thesis.

Chapter-2 This chapter presents a review of Literatures on Piano Key Weir (PKW). Different aspects of this weir like structural, economic, aeration, sedimentation and self-cleaning have been discussed and compared with its counterparts.

Chapter-3 This chapter presents the Numerical Methodology and setup for our numerical study of the Mathematical Model of PKW undertaken in the present work. The chapter discusses the Black Box model of the ANSYS platform and the mechanism behind the numerical solution strategy.

Chapter-4 This chapter deals with the use of computational fluid dynamics to study the head-discharge study of Piano Key Weir (A-type) from Literature for low heads. Water surface profile and longitudinal velocity profile hs been discussed, and the numerical study validated and verified by the knowledge from literature.

Chapter-5 This chapter deals with an experimental and numerical study of discharge capacity and sediment profile upstream of Piano Key Weirs with different plan geometries. Rectangular (RPKW) and Trapezoidal PKWs (TPKW6 & TPKW13) have been studied experimentally in Flume F1. A numerical study has been done to identify the critical areas where the sediment scouring is highest. The study of vertical velocity component of velocity through numerical study at these critical points has been further taken up to study the variations in PKWs of different plan geometries.

Chapter-6 This chapter deals with the study of flow over the piano key weir for two plan forms: RPKW AND TPKW9. Head-discharge relationships have been studied experimentally and numerically in free-flow conditions. The experiment was conducted on a flume of 0.984 m width. The tailgate of the channel was rendered partially closed to study the outlet key submergence and their impact on the discharge efficiency of PKW.

Chapter-7 This chapter deals with summary, conclusions and scope for future work. The chapter is followed by a list of publications and required permissions for reprints.

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