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Design the stilling basin to form hydraulic jumps on sloping apron

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Abstract

Utilizing a combination of field measurements, hydrodynamic modeling, and ecological assessments, the research examines changes in flow velocity, sediment transport, and water quality resulting from channel modifications. The study also explores the subsequent effects on ecosystem services, including habitat provision, water purification, and flood regulation. The findings reveal that while certain modifications may enhance specific hydraulic functions, they often lead to unintended ecological consequences, such as habitat degradation, loss of biodiversity, and reduced water quality. Furthermore, the study highlights the trade-offs between improving hydraulic efficiency and maintaining ecological integrity. It demonstrates that sustainable channel management requires a balanced approach that considers both engineering objectives and environmental impacts. The research emphasizes the importance of incorporating ecosystem-based approaches in the design and implementation of channel modifications to preserve or enhance ecosystem services.

Keywords: Hydrulic construction, stilling basin, Hydraulic Jumps, ecosystem

Introduction

An evacuation system is put in place to manage the controlled output of the flow, as hydraulic constructions like barrages installed in natural riverbeds alter the natural flow. Spillways are systems that change supercritical flow into subcritical flow using a stilling basin. As a rule, the water outflow has to have its kinetic energy dispersed since, otherwise, it would induce erosion downstream. In order to connect the pool's outflow pipe to the river's natural level, this dissipation takes place by means of a hydraulic leap that is formed in the stilling basin. Pools like this are often horizontal because they guarantee subcritical flow at the outflow; but what happens to rivers with steep banks when subcritical flow isn't present? A supercritical regime is characterised by torrential flow in the catchment structures situated in rivers with steep slopes. The stilling basin's subcritical regime becomes supercritical once again as a result of the disparity in slopes between the river's natural gradient and the bottom.

Here, turbulence and continuous waves are caused by potential energy that is higher than the natural course, which is generated near the exit of the stilling basin. According to Chanson, the difficulty of a hydraulic leap lies in the transfer of turbulent flow, the formation of large-scale vortices, and the containment of air bubbles at the jump's apex. He adds that the most difficult parts of designing a weir to prolong its life are energy transfer and dissipation. Also, the structure is directly impacted by vibrations caused by the chaotic leaps of stilling basins downstream of the weir, as shown by Legono, Hambali, and Krisnayanti. Thus, it is necessary to find the best way to construct a stilling basin so that the energy dissipation of supercritical flow may be guaranteed at the exit and returned to the river's normal flow.

The authors of the cited study found that hydraulic jumping in sloping screeds yields high quality efficiency results similar to horizontal screeds, and they also found that the maximum energy reduction in relation to the increasing slope of the channel was 45%. Computing the flow in a sloping stilling basin using computational fluid dynamics (CFD) software yields accurate results. By developing a physical and numerical model of the dam spillway, Thu

Hien was able to demonstrate that, by using Navier-Stokes' equations, CFD can faithfully replicate several real-world fluid events in the stilling basin. In order to achieve the natural supercritical flow of the river, it is necessary to conduct experimental studies using numerical models of stilling basins with sloping bottoms. This will ensure the accuracy and dependability of energy dissipation during supercritical flow at the pool exit. The hydraulic structure's performance and safety would both be enhanced as a result of this. An ideal solution for the construction of stilling basins is proposed in this study by modelling the flow behaviour in an energy dissipation structure situated in a high-slope river.

Literature Review

Kumar, A. Uday *et al*. (2020) [1]. The Krishna River has seen changes to its flow regime and the effects of human intervention on river ecosystems. Optimal maintenance of the river's Environmental Flow (EF) is essential for reestablishing its ecosystem after damage. This study intends to measure the Environment Flow Requirements (EFRs) and the Hydrological Alteration (HA), commonly called flow changes, at five separate dam sites along the Krishna River. Flows before and after construction may be measured at five-gauge stations located downstream of these five dams. The study does not include flow data that are impacted by natural climatic fluctuations so that the impacts of human activity can be isolated. This EFR is calculated with the use of the Global Environmental Flow Calculator (GEFC) by looking at statistical connections between the ecological indicator and the Krishna River's flow regime. After the dam has been built, in the post-impact phase, HA is used to analyse the differences in the proposed EFRs. Hydrologic indicators like water depth and velocity may be calculated by entering expected EF values into a model called HEC-RAS, which is part of the Hydrologic Engineering Centre. The habitation analysis's goal is to find out whether the hydraulic indicators in the study area are good places for aquatic animals to live. In the post-impact era, the Krishna River failed to maintain the requisite EFRs for more than 43% of the time, according to the HA research. Hydraulic studies show that the proposed EFR is providing water depths of 0.23 and 3.16 metres at velocities of 0.12 and 1.08 meters per second throughout the basin. Under the Srisailam and Nagarjuna Sagar dams, inhabitation studies have shown that the GEFC approach offers better living circumstances. A variety of ideal living places may be found in the Ujjani, Narayanapur, and PD Jurala dams.

Standen, Kathleen *et al*. (2020) [2]. By trapping flow from intermittent streams, managed aquifer recharge (MAR) systems aim to enhance recharge to the underlying aquifer. This is achieved by various in-channel alterations. This report presents a reanalysis of the features and success factors of 79 recharge dams across the globe in order to assess the practicability of using these approaches in Europe. Natural flood control strategies, which reduce flood flow and enhance recharge, are among the other in-channel changes explored narratively in this study. One example is dams that store sand. This study presents findings from a worldwide perspective that suggest in-channel MAR solutions have the potential to improve groundwater quality and increase water availability. This might be useful in resolving problems with aquifers in hydraulic linkages with temporary streams in Europe. Therefore, in-channel MAR might be considered as a solution to address aquifer water quality issues, fix groundwater shortages, or reduce groundwater problems like salt intrusion to meet the requirements of the Water Framework Directive (WFD).

Bertalan, Laszlo *et al*. (2019) [3]. A comprehensive assessment of the regional and temporal variations in river channel alterations and meander formation is required for efficient floodplain management. It is unusual to see alluvial rivers in Central Europe that follow a pattern similar to a natural river. Due to a lack of comprehensive management, these rivers are free to move throughout their floodplain, eroding both agricultural and natural regions. Given the paucity of literature on channel dynamics in river systems such as the Sajó River (Slovakia-Hungary), it is useful to characterised the channel morphometric features throughout decadal periods. Along with studying the geomorphic processes, we also need to investigate what they mean for environmental management. The 124-kilometer-long Sajó River in Hungary has been the subject of morphological research over eight distinct time periods, spanning 1952–2011. Using a database that included historical aerial pictures, orthophotographs, and topographical maps, we conducted GIS-based studies to quantify the rate and area of channel modifications, bend formation, and erosion/accretion. We have calculated many morphometric parameters on the bend scale, such as bend length, chord, amplitude, and radius of curvature, to assess the evolutionary trajectory of reaches. We looked at hydrological time series data to see whether it may be involved in the processes. Using the existing GIS-data on natural components and human involvement, twelve separate reaches were discovered with similar traits; six of these reaches were determined to be natural. Morphometric features indicate that the sinuosity of the reaches increased, despite the fact that the planform grew more spatially concentrated and channel widths were narrower in most of the reaches. Although artificial cutoffs mostly function to simplify reaches, there have been occasions when they have accelerated the development of downstream bends in subsequent years. Erosion and accretion were more active when the discharge was higher than the effective discharge, but this effect diminished as the study period came to a close. Substantial bank security procedures and artificial cutoffs were put in place by 1980 to try to stop channel shifting.

Mendoza-Lera, Clara *et al*. (2016) [4]. It is common practice for river managers to restore hydrological exchange with the hyporheic zone, also known as hyporheic flow, in order to improve habitat quality and ecological functioning, such as biogeochemical processing and pollutant retention, through increasing the mass transfer of solutes, such as nutrients, carbon, oxygen, and nitrate. However, even when hyporheic flow is enhanced, there are often no noticeable alterations in biogeochemical processes. A few of these seeming contradictions arise from the simplistic belief that biogeochemical processes and hyporheic flow are closely connected. Our alternate model proposes a non-linear relationship between hyporheic flow and biogeochemical processes. We hypothesis that the hyporheic hydraulic conductivity governs the biogeochemical processing in the zone, since different hydraulic conductivities have different solute mass transit and colonization area available. This suggests that the function is Gaussian in nature. First, we introduce the conceptual model and discuss its potential uses; next, we discuss the potential outcomes, paying specific attention to hyporheic studies and river restoration.

Hydrological processes and flood hazards are two of several human-environmental system factors that may be significantly impacted by changes in land use. In order to effectively manage human-environmental interactions and solve possible environmental problems like floods, it is essential to have information about future changes in land cover. This research uses a case study in northeast Indiana, USA, to evaluate how future changes in land cover would affect flood inundation. To forecast land cover changes, generate future maps, and apply statistical validation techniques, a Cellular Automata Markov (CAM) model is used, which integrates Geographic Information Systems (GIS) with Python. The results of the land use maps are then fed into a hydraulic model called HEC-RAS. This model is used to examine various flooding consequences during a design storm by implementing the rain-on-grid routine. There was an increase in the potential flood extent for even marginally more urbanised and deforested regions, according to the data. Also, using a geographical Ecosystem Services Valuation (ESV) model, we may put a dollar amount on the effects of these projected changes in land cover. According to the results, the 'lost' value might reach 1.5 million USD in 2051 if certain land uses (mostly wetlands and woods) are replaced by development, barren land, or even agricultural space. For the first time to our knowledge, this work integrates land cover prediction with hydrologic-hydraulic modelling and spatial ESV, revealing future changes, risks, and possible economic losses, respectively. This integration gives the study its originality. Because all of the data and scripts are publicly accessible and this application just utilises the bare minimum to do the analysis, it is easy to replicate and transfer the results to other settings.

Determination of appropriate C_d for free flow condition on horizontal apron

A constant value of Cd = 0.623 is used in the mathematical design of the stepped weir to account for the free flow condition, as per the Francis formula. Laboratory tests have helped to experimentally demonstrate the validity of the same. Analytical estimation of Cd is very unlikely due to the many types of errors associated with the flow conditions. Some of the features upstream of the stepped weir include hydraulic jump and the turbulence that goes along with it. The stepped weir has a short upstream reach since its length is proportional to the stilling basin's length. The primary objective of the research is to experimentally determine the suitability of Cd based on the suitability of the hydraulic jump position, which is susceptible to errors caused by specific assumptions in the mathematical design of the weir. Since Cd is an implicit function, it must be assumed initially. It is possible to experiment with different step widths to see what works best for the weir if its performance is subpar. Testing in a controlled environment, such as a laboratory flume, is being considered. The first two meters of the canal are elevated to provide free flow conditions over the stepped weir. This was accomplished by inserting a 5-centimeter-high wooden platform into a flume. Views of the real setup in the laboratory are shown in Fig. 1

View from downstream Right hand side view

View from downstream with free flow from the weir

Fig 1: Photographs showing raised platform in the laboratory tilting flume and free flow conditions created over the stepped weir

Common parameters for which weirs are designed are H=0.4m, B=0.3m, Q_{max}=0.01 m^3/s, Q_{min}=0.002 m^3/s, y'=0.015m. Three weir models, each for C_d=0.6, 0.65 and 0.623 are designed. As per present practice, energy dissipators are designed for the design discharge conditions and their performance is tested at lower discharges (Vittal and Al-Garni 1992). Generally, apart from design discharge, the performance is tested at 3 lower discharges which are 75%, 50% and 25% of design discharge. To increase the accuracy, it is proposed to consider 10 lower discharges and reduce the lowest discharge to 20% of design discharge. Thus, including design discharge, there would be total 11 discharges. Thus in the proposed stepped weir, there are 11 steps corresponding to 11 discharges. Tables .1(a, b and c) give the geometry of these weirs and other parameters related to hydraulic jump.

Table 1: Output of Mathematical Procedure for Laboratory Data (Horizontal apron and C_d = 0.6)

Sr. No.	Q m^3/s	y_1 m	y_2 m	H m	Fr1	b m
1	0.0020	0.0024	0.0605	0.0455	18.3350	0.1162
2	0.0028	0.0033	0.0714	0.0564	15.4960	0.1387
3	0.0036	0.0043	0.0807	0.0657	13.6661	0.1519
4	0.0044	0.0052	0.0889	0.0739	12.3614	0.1629
5	0.0052	0.0062	0.0965	0.0814	11.3709	0.1723
6	0.0060	0.0071	0.1034	0.0884	10.5857	0.1808
7	0.0068	0.0081	0.1098	0.0948	9.9435	0.1885
8	0.0076	0.0090	0.1159	0.1009	9.4056	0.1957
9	0.0084	0.0100	0.1216	0.1066	8.9466	0.2023
10	0.0092	0.010947	0.1270	0.1120	8.5487	0.2087
11	0.0100	0.011899	0.1322	0.1172	8.1997	0.2147

With C_d = 0.6, the performance of weir is tested for boundary conditions of discharge, that are Q_{min} and Q_{max} to check the possibility of jump formation and the adequacy of its location. It is presumed that if the weir performance it unsatisfactory over these extreme discharges, then it would probably be unsatisfactory for the intermediate discharges also. The jumps are found to be shifted in the downstream direction for both the discharges. This shows that the area of flow section of stepped weir is larger and need to be reduced. This can be done by reducing the step widths which requires increase of C_d as b varies inversely with C_d.

Table 2: Output of Mathematical Procedure for Laboratory Data (Horizontal apron and C_d = 0.65)

Sr. No.	Q m^3/s	y_1 m	y_2 m	H m	Fr1	b m
1	0.0020	0.0024	0.0605	0.0455	18.3350	0.1073
2	0.0028	0.0033	0.0714	0.0564	15.4960	0.1280
3	0.0036	0.0043	0.0807	0.0657	13.6661	0.1403
4	0.0044	0.0052	0.0889	0.0739	12.3614	0.1504
5	0.0052	0.0062	0.0965	0.0814	11.3709	0.1591
6	0.0060	0.0071	0.1034	0.0884	10.5857	0.1669
7	0.0068	0.0081	0.1098	0.0948	9.9435	0.1740
8	0.0076	0.0090	0.1159	0.1009	9.4056	0.1806
9	0.0084	0.0100	0.1216	0.1066	8.9466	0.1868
10	0.0092	0.010947	0.1270	0.1120	8.5487	0.1926
11	0.0100	0.011899	0.1322	0.1172	8.1997	0.1981

In the second trial another stepped weir is designed with C_d = 0.65 and tested in a similar manner. During this, the jumps are found to be drowned. Hence for the third trial C_d = 0.623 is adopted and accordingly, tests are taken.

For stepped weir with C_d = 0.623, the hydraulic jumps have formed inside the basin and the fronts of jumps in all the cases were found to be located near the sluice gate. Thus C_d = 0.623 is confirmed empirically for the condition of free flow over the weir. For higher submergences ($S_r > 0$), the coefficient of discharge will decrease and takes the form of modified coefficient of discharge ($C_{dm} = k_s C_d$, where $k_s<1$). In this case, k_s is a submerged flow coefficient for stepped weir which is newly introduced. Determination of C_{dm} based on K_s is explained below.

Table 3: Output of Mathematical Procedure for Laboratory Data (Horizontal apron and C_d = 0.623)

Sr. No.	Q m^3/s	y_1 m	y_2 m	H m	Fr1	b m
1	0.0020	0.0024	0.0605	0.0455	18.3350	0.1119
2	0.0028	0.0033	0.0714	0.0564	15.4960	0.1336
3	0.0036	0.0043	0.0807	0.0657	13.6661	0.1463
4	0.0044	0.0052	0.0889	0.0739	12.3614	0.1569
5	0.0052	0.0062	0.0965	0.0814	11.3709	0.1660
6	0.0060	0.0071	0.1034	0.0884	10.5857	0.1741
7	0.0068	0.0081	0.1098	0.0948	9.9435	0.1816
8	0.0076	0.0090	0.1159	0.1009	9.4056	0.1884
9	0.0084	0.0100	0.1216	0.1066	8.9466	0.1949
10	0.0092	0.010947	0.1270	0.1120	8.5487	0.2010
11	0.0100	0.011899	0.1322	0.1172	8.1997	0.2067

Experimental Observations for Hydraulic Jump on Horizontal Apron

Using a mathematical approach, the geometrical parameters of the weir sections are determined. The weir sections are made of perspex that is 1 cm thick once the practical weir geometries have been determined. Figure 2 shows the weir parts for the horizontal apron case. Over a whole range of discharge and with certain average submergence ratios, experiments are conducted to investigate the hydraulic leap that occurs when the weir sections are present. Table 3 displays the outcomes.

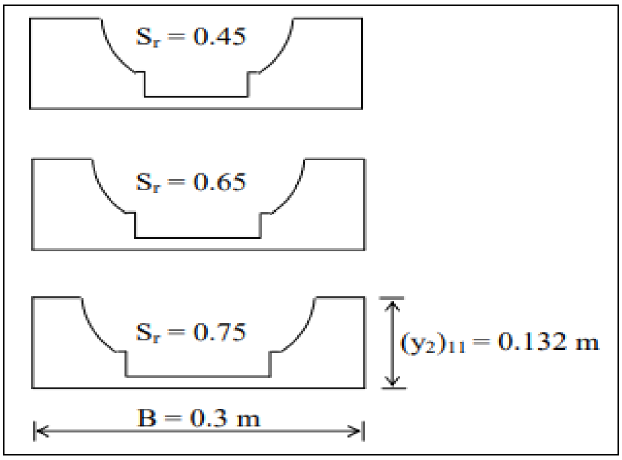


Fig 2: Weir sections for 3-average submergence ratios

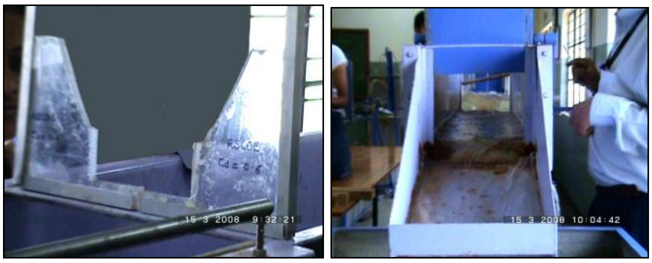
Fig. 2 shows photographs demonstrating details of experimental trials taken in laboratory.

Photographs showing views of Experimental Setup

Photographs showing close views of flow conditions in the tilting flume

Photographs showing hydraulic jump formed very close to the sluice gate (Section and Plan)

Fig 3: Photographs showing details of experimental trials taken in laboratory (Horizontal Slope)



Experimental condition under Natural Tail Water Submergence of 40 – 50% in the Laboratory Flume

Experimental condition under Artificial Tail Water Submergence of 60 – 70% in the Laboratory Flume

Experimental condition under Artificial Tail Water Submergence of 70 – 80% in the Laboratory Flume

Fig 4: Photographs showing details of experimental trials taken in laboratory (Horizontal Slope)

Table 4: Summery of experimental results for three weir sections

Q (m^3/s)	y_1(m)	y_2 (m) (ideal)	y_2 (m) for weir with C_{dm}= 0.6	y_t (m) for weir with C_{dm}= 0.6	y_2 (m) for weir with C_{dm}= 0.55	y_t (m) for weir with C_{dm}= 0.55	y_2 (m) for weir with C_{dm}= 0.5	y_t (m) for weir with C_{dm}= 0.5
0.0100	0.0132	0.132	0.124	0.070	0.123	0.090	0.126	0.105
0.0088	0.0121	0.124	0.120	0.067	0.122	0.086	0.120	0.098
0.0075	0.0100	0.115	0.110	0.061	0.112	0.079	0.112	0.089
0.0067	0.0095	0.109	0.107	0.059	0.110	0.076	0.109	0.085
0.0052	0.0070	0.096	0.092	0.050	0.091	0.063	0.093	0.071
0.0048	0.0063	0.092	0.087	0.046	0.085	0.057	0.085	0.064
0.0024	0.0032	0.066	0.063	0.034	0.062	0.043	0.062	0.047

Detailed experimental results for weir sections showing various parameters like (prejump – depths, velocities and Froude numbers), (post jump – depths, velocities and Froude numbers), (tail water – depths, velocities and Froude numbers), (tail water – depths, velocities and Froude numbers without designed weir), percentage submergence ratio, percentage energy dissipation, height of jump and length of jump are given in Tables – C- 1, C-2 and C-3 of Appendix C. Fig. 5 shows plot of ideal and experimental JHC and experimental TWRC. A satisfactory agreement is found between the ideal and experimental values of y_2 as correlation coefficient is found to be in the range of 0.98 to 0.99. The experimental findings are discussed in detail at the end of this chapter, in the section 'results and discussions'.

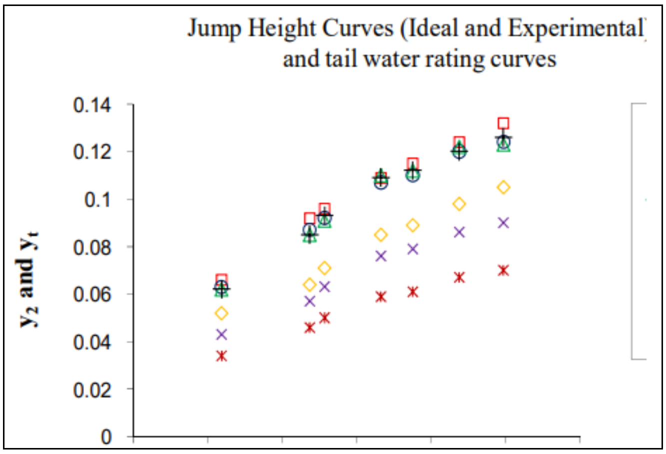


Fig 5: Comparison of TWRC (y_t), IJHC (y_2-ideal) and FJHC (y_2-exptl)

Conclusion

It is essential to build the stilling basin with the operational circumstances in mind. A distillation basin's efficiency is critical, hence it has to be able to handle discharges ranging from 20% to 100% of the design discharge. This can only be accomplished by strategically placing the hydraulic jump for various outputs and the associated depths of the tail water. To achieve this goal, the stilling basin should have the following features. To sum up, the thesis introduces a novel design for a stilling basin for tail water insufficiency that uses hydraulic jumps. The most crucial and infamous element, tail water depth, is also addressed by providing a general solution in the shape of a rectangular wide crested constructed weir.

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