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Develop a new technique to control location of forced hydraulic jump in a rectangular channel

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Abstract

Channel modifications, such as river engineering, dredging, and artificial embankments, are often implemented to manage water flow, prevent flooding, and support navigation. However, these interventions can significantly alter the hydraulic characteristics of water bodies, leading to profound effects on the ecosystem services they provide. The effects of different channel changes on hydraulic dynamics and the ecological functions of river systems. The study also explores the subsequent effects on ecosystem services, including habitat provision, water purification, and flood regulation. An improved comprehension of the intricate interplay between hydraulic engineering and ecological systems. It provides practical recommendations for policymakers, engineers, and environmental managers on how to mitigate the negative effects of channel modifications while maximizing the benefits for both human and natural systems. The research underscores the need in order to accomplish integrated water management strategies that balance ecological and hydrological factors for the benefit of future generations sustainability of riverine environments.

Keywords: Hydraulic Jump, Technique, ecological systems, environments

Introduction

Hydraulics, meaning "water," is both a technical discipline and an applied science that draws on chemistry, engineering, and other fields to study the mechanical characteristics and practical applications of liquids. To put it simply, hydraulics deals with liquids while pneumatics deals with gases. Hydraulics, an applied branch of engineering that makes use of fluid qualities, is theoretically grounded in fluid mechanics. When it comes to fluid power, hydraulics is all about using pressurized liquids to generate, regulate, and transmit power. Subjects covered in hydraulics include fluid dynamics, pipe flow, dam design, and fluid control circuits; they appear in a variety of engineering and scientific courses. Both the circulatory system and the erectile tissue naturally use hydraulic principles. Rivers, canals, lakes, estuaries, and oceans all exhibit free surface flow, which is the focus of free surface hydraulics.

The traditional hydraulic leap, often known as a jump created in a horizontal, broad rectangular canal with a smooth bed, has been the subject of much research. The hydraulic leap was examined experimentally and conceptually by Hager. In a horizontal rectangular flume with smooth side walls, Hughes investigated the hydraulic jump characteristics over many artificially roughened test beds. Evidence from experiments shown that roughness at the border of a hydraulic jump shortens its subsequent depth and length, with the shortenings being correlated with both the Froude number and the roughness degree. A suggested approximation for a theoretical hydraulic jump equation was found to match well with the observed features, and the observed characteristics were congruent with theory. A turbulent hydraulic leap over a rectangular channel with a rocky bed was studied by Afzal in terms of its stream-wise flow structure.

Literature Review

Mastrorilli, Marcello *et al*. (2018) [1] Droughts and floods are influenced by eco-hydrological processes, which are in turn affected by land use. Alterations to land use have an effect on ecosystems and the hydrologic services they provide. Hydrological services are the focus of this investigation, which intends to measure water resources, pollution loads, land retention capacity, etc. Quantitative evaluation data is used to determine the monetary value of ecological services. At the ecosystem level, hydrological services may be estimated by assigning a monetary value to the hydraulic system and natural resources. The proposed method was tested in the "Bonis" basin in Italy's Calabria Region. The analysis takes four possible land use scenarios into account: (i) a well-vegetated baseline; (ii) shifting the forest canopy; (iii) adjusting the forest-to-farm ratio; and (iv) introducing impermeable zones. Model results reveal that water balance and, hence, provided economic value are very sensitive to changes in forest area status. A little change in the total amount is produced by narrowing the impermeable zones. Soil erosion, water storage capacity, and water harvesting are all impacted by increasing the share of arable land to 50% while decreasing forest cover. The suggested method is a good choice for land planning.

Hooke, J. (2023) [2]. When plants grow in the bed of dryland, transient channels, they may have a disproportionately large influence on hydraulics and processes. We require data on flow impacts and vegetation dynamics to understand the hydraulics, feedback effects, and ecological dynamics for management and modelling purposes. The purpose of this analysis is to determine the thresholds for plant damage and destruction, evaluate recovery rates, and quantify the effects of different vegetation densities and heights on channel hydraulics by looking at evidence from sites in southeast Spain that have been monitored for decades in relation to an extreme flood that occurred in September 2012. The data on plant cover, health, and heights were examined using repeated quadrat measurements in conjunction with cross-section topographic surveys conducted before, during, and after the 2012 flood, as well as with measurements of flow stage. The flood event reset the vegetation by destroying most of it, including the dominating Retama. We have determined the shear stress thresholds that will cause plant death and removal. Different areas have had different rates of recovery; for example, regrowth is minimal in high floodplains and major channels, but robust on bars. There is a predicted big influence on the hydraulics of flow from the various degrees of plant cover and height. The findings provide credence to the idea that thick plant cover, via lowering flow rates, decreasing erosion, and boosting sedimentation, might be a very successful channel management tool.

Biswas, Mery & Raha, Adrija. (2022) [3]. The study of a channel's free surface flow, which varies with the seasons, is known as open channel hydraulics. Extreme conditions in terms of stream power, sheer stress, and velocity are shown by the monsoonal hydrological features of rivers in the foothills of the Himalayas. Upstream, between, and after river crossings such as Lish, Gish, and Chel, these features have changed significantly. From the years 1913 to 2021, the riverine topography underwent remarkable changes as a result of the bridges, including channel shifting close to, upstream of, and downstream of them. The monsoon season brings an uptick in stream strength and velocity close to the Chel River's rail and road bridge, then the Gish and Lish rivers. According to the research, a greater stream power value (20,489.06) corresponds to a faster velocity, which in turn causes significant silt deterioration along the riverbed and bank. High stream power continually induces the transfer of sediments further downstream from the foothill. A decline in the competence of sediment load transport together with streamflow is indicated by low stream power levels. From 1965 to 2021, the riverbed topographic elevation of the Lish climbed by about 1.3 m and that of the Gish by about 1.0 m, respectively, as a result of the slow aggradation of sediments caused by low stream power and velocity. Because scouring and degradation mechanisms are so dominant, River Chel has undergone a negligible aggradation process. It is possible that the building of road and rail bridges over the channel is to blame for the differences in the pattern of stream power, shear stress, and velocity in various parts of the rivers. There is a higher concentration of suspended silt in the Gish and Lish rivers than in the Chel. The distance between the rail bridge and the riverbed is at its narrowest along the Lish.

Polasky, Stephen & Nelson, Erik & Pennington, Derric & Johnson, Kris. (2011) [4]. Ecosystems throughout the globe are being profoundly affected by changes in land use. Ecosystem services, biodiversity protection, and landowner returns are all significantly affected by changes in the size and make-up of ecosystems including wetlands, grasslands, and forests. Although changes in private landowner returns can usually be evaluated, changes in ecosystem service supply and value, as well as the provision of biodiversity protection, have proven more difficult to quantify. From 1992 to 2001, land-use change in Minnesota had a significant impact on ecosystem services, biodiversity habitat, and landowner returns. To evaluate these changes, we used a spatially explicit integrated modelling method (InVEST). Both real land-use change and a variety of hypothetical land-use change scenarios are considered and assessed. We discover that the ranking of baseline and alternative land-use scenarios does not align when it comes to the creation of net societal benefits, which is the sum of private returns to landowners and the value of ecosystem services. For landowners, the best-case scenario is one in which there is widespread agricultural growth. Nevertheless, due to significant consequences on water quality and losses in stored carbon, this scenario had the least net societal benefits compared to any of the others. Additionally, the greatest loss in habitat quality for terrestrial biodiversity and forest songbirds occurred under this scenario. Our findings highlight the significance of attaching incentives that fairly represent societal benefits to land-use and land-management choices that take ecosystem services into consideration. Ecology, biodiversity, land use, private landowner returns, net societal benefits, and ecosystem services are all related terms.

Birkhofer, *et al*. (2015) [5]. To bring attention to the importance of biodiversity and ecosystem protection, the idea of ecosystem services was first proposed as a way to quantify the societal benefits produced by natural ecosystems. Ecologists doing empirical or model-based research on ecosystem services face a number of obstacles and possibilities that we highlight in this article. The lack of an ecosystem service concept developed within the framework of controlled systems is the root cause of the first obstacle. Ecologists can't recommend policies that would help service-providing creatures and the services they provide unless they can determine the impact of human initiatives. The second obstacle is the fact that ecological studies often gather indicators of ecosystem services; nevertheless, there is a lot of uncertainty about the underlying ecological processes of these services, thus it may be difficult to assess the links between them. We propose a framework of indicators that encompasses service-providing units, ecosystem management, and landscape transformation as the foundation for evaluating ecosystem services. We don't have a broad statistical framework to handle the third obstacle, which is our inadequate knowledge of the nature of interactions across services. Ecologists must determine whether services are directly related or react to a common cause in order to manage the providing of services within an ecosystem. Lastly, studies examining the relationship between biodiversity and ecosystem services tend to concentrate on services that operate at small geographical or short temporal dimensions, while studies aimed at safeguarding these services tend to be focused on services that provide benefits at large spatial scales. To provide a comprehensive picture of the many ways in which nature contributes to human flourishing, ecological studies must take into account a variety of geographical and temporal dimensions. Ecologists have a once-in-a-lifetime chance to disseminate knowledge on how to preserve the advantages of nature by tackling these difficulties in the future.

Materials and Methods

To achieve appropriate location of hydraulic jump in rectangular channel of width B, it is essential to consider input parameters which govern location of jump. Fig 1 demonstrates definition sketch of hydraulic jump in rectangular channel with horizontal slope.

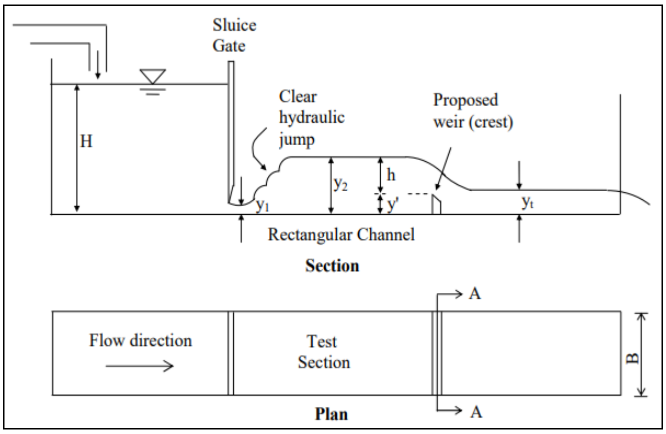

Fig 1: Definition sketch of hydraulic jump in rectangular channel

Hydraulic leap is affected by the following variables: total head on upstream of the sluice gate (H), depth before the jump (y1), depth after the jump (y2), weir crest height (y'), head over the weir crest (h), and tail water depth (yt). The hydraulic leap phenomena are governed by the supercritical Froude number Fr1, another nondimensional significant quantity.

The 'jump height curve' (JHC) and the 'tail water rating curve' (TWRC) are formed by plotting the variables y2 and yt on the Y-axis, respectively, with discharge Q on the X-axis and these two variables.

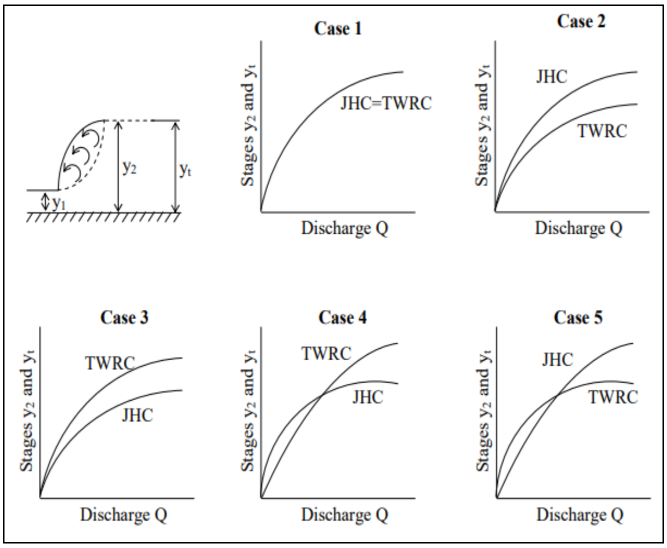

Fig 2: Classification of tail water conditions for the design of energy dissipator

At varying discharges, five distinct situations would emerge depending on the respective magnitudes of y2 and yt. The disparity between y2 and yt for a certain discharge is represented by the vertical distance between JHC and TWRC. At the vena contracta of a supercritical flow, a hydraulic leap develops when this difference is zero, yt = y2. This becomes an ideal situation (Case^{-1}) that guarantees the production of a clear hydraulic leap at the vena contracta for all discharges if it is attained for all of them. No fixtures in the stilling basin are necessary in this case; a horizontal apron with the top at river bed level would do. In actuality, however, such circumstances are quite uncommon.

When out in the field, you'll usually see tail water depths that are on the higher or lower side. In some cases, they are partially on the lower side and partly on the higher side over the whole discharge range, and vice versa. Therefore, it has an immediate impact on where the hydraulic jump is placed on the apron. When the value of yt is less than y2 in Case - 2, the hydraulic leap is said to be swept up jump because it sweeps out of the basin. In such a scenario, the leap can originate in the downstream channel far from the stilling basin, or it might develop far from the toe of the spillway yet stay partially on the apron. In case yt > y2 (Case -3), the hydraulic leap is called a submerged or drowned jump because it rides on a sloping spillway surface. Here, the apron could be scoured by a high-velocity flow that stretches over it for a long distance. Occasionally, it could reach all the way to the end sill. Also, according to Bower and Toso (1988), large-scale pressure changes may be seen in the drowning leap. Case-4 shows that for lower discharges, yt is less than y2, whereas case-5 shows that for lower discharges, yt is more than y2, and for all other discharges, yt is less than y2.

In this investigation, we zero in on the second case of tail water deficit. When there is a tail water deficit at lower flows, it is somewhat relevant to case-4 as well. As seen in Case 2, the tail water depth is less than the post jump depth over the entire discharge range. As the discharge increases, the disparity between these two depths widens.

Consequently, the jump's apron position changes and its toe travels further and farther from the targeted point, which is the toe of the spillway or sluice gate. There is a linear decrease in energy dissipation as the leap deviates from its target destination.

Spillways on flanks are the most common places to have tail water deficit. Since the tail channel's primary function is to redirect floodwaters back to the main river channel, it is steeper than the original channel due to the substantial elevation change over a relatively short distance. The result is usually faster speeds and shallower flows in the tail channel. Because there aren't enough tail water depths to create the leap, it tends to wash out.

Since the drowned leap is safer than the swept-up jump, a stilling basin of the hydraulic jump type with a depressed horizontal apron and an end sill is ideal for low-discharge applications. A horizontal apron, which may be either level with the riverbed or slightly depressed, with a rectangular wide crested weir, sometimes called a "end weir," at its end is another option. Water entering the tail channel carries very high amounts of leftover energy due to the fact that flooded leaps release less energy than clear jumps. From what we can tell, the channel floor height immediately downstream of the end weir and the apron level immediately upstream are assumed to be identical in this research. In some instances, the sole adjustment made to bring the y2 and yt levels into alignment is a reduction in the apron height. However, reducing the apron height also necessitates the expenditure of more excavation.

A general solution to the issue of tail water insufficiency might be achieved by considering the range of tail water submergence while designing an end weir geometry that can accommodate a broad range of discharges. The goal of the suggested solution is to go from the current state of tail water insufficiency (Case-2) to the ideal state of affairs (Case-1).

It is well-known that a single rectangular suppressed weir, regardless of its height, can only handle a single specific discharge. The weir will sweep out if subjected to a greater discharge rate when it was built for a lower one. A drowned leap, as seen in Figure 3 will occur if a weir that is intended for high flow is subjected to reduced discharge. What this implies in practice is that, under constant head, there is a one-to-one relationship between the discharge and the final weir height. But, when a contracted weir is planned, the crest height is reduced, and a width of weir is produced for each discharge that is inversely proportional to the discharge. To sum up, widths change even when crest heights remain the same, and widths change even when crest heights remain the same. Designing single-end weir geometry such that it provides the impact of all such individual weir heights or widths is important to meet the study's purpose. Consequently, a rectangular stepped weir might work here. Broad crested weirs, which are gravity structures, are often used as end weirs on fields. They may also be supplied as sharp crested weirs for use in other smaller projects. Because of their high modular limit (0.85, according to the USBR Water Measurement Manual), wide crested weirs are not as affected by submergence effects. Because sharp crested weirs are more vulnerable to the submergence effect than other types of weirs, research into this phenomenon is necessary. Accordingly, sharp crested weirs are used to start the investigation. As a case study tool, broad crested weirs are used.

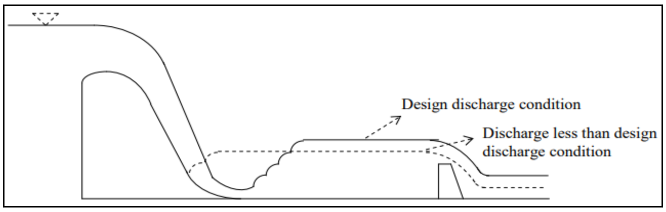

Fig 3: Location of hydraulic jump at design and lower discharge for the end weir designed for design discharge condition

Data analysis

Stepped Weir Geometries for Submerged Flow Conditions on Horizontal Apron

Flume details: (refer fig. 3)

1. Tilting flume in the form of rectangular channel made up of mild steel (walls and bottom) except the first half portion which has perspex side walls.
2. Length of test section of flume = 4 m
3. Width of flume (B) = 0.3 m
4. Height of flume = 0.45 m
5. Slope = horizontal

Experimental conditions

1. Head on upstream of sluice gate (H) = 0.4 m
2. Range of discharge = 0.002 m^3/s (Q_{min}) to 0.01 m^3/s (Q_{max})
3. Average tail water submergence
4. ratios (S_r) considered = 0.45, 0.65 and 0.75
5. Modified coefficient of discharge C_{dm} = 0.6, 0.55 and 0.5
6. Location of stepped weir = 2 m downstream of sluice gate

Sluice Gate

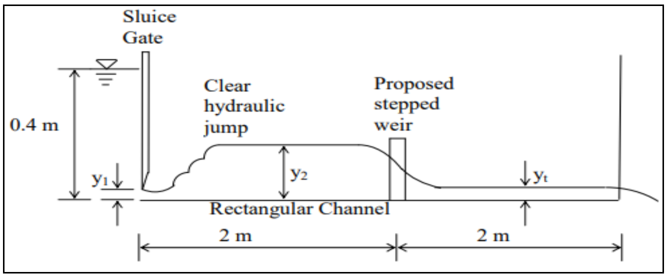

Fig 4: Schematic of Experimental Setup

Table 1: Output of Mathematical Procedure for Laboratory Data (Horizontal apron) (S_r = 0.45, k_s = 0.96, C_{dm} = 0.6, y' = 0.015m)

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

Table 2: Stepped Weir Geometries for three different submergence ratios

y_2 m	Widths of steps b (for S_r = 0.45) (k_s=0.96), (C_{dm} = 0.6) m	Widths of steps b (for S_r = 0.65) (k_s =0.88), (C_{dm} = 0.55) m	Widths of steps b (for S_r = 0.75) (k_s =0.80), (C_{dm} = 0.5) m
0.0605	0.1162	0.1268	0.1394
0.0714	0.1387	0.1513	0.1664
0.0807	0.1519	0.1658	0.1823
0.0889	0.1629	0.1777	0.1955
0.0965	0.1723	0.1880	0.2068
0.1034	0.1808	0.1972	0.2170
0.1098	0.1885	0.2056	0.2262
0.1159	0.1957	0.2135	0.2348
0.1216	0.2023	0.2208	0.2428
0.1270	0.2087	0.2276	0.2504
0.1322	0.2147	0.2342	0.2576

Table 2 gives geometry and Fig. 5 shows photograph of 3 weir sections which are fabricated in perspex. Though mathematical procedure renders stepped weir with 11- steps, practical geometry is adopted for final section. Details about practical geometry are given below.

Practical Geometry of Stepped Weir

Proposed stepped weir in the study has 11 steps. That means 11 risers and 11 treads on either side. Therefore, on either side, there are 22 sharp edges. As the sharp edges and corners may invite a problem of cavitation, it is customary to join the steps by a smooth curve. The middle step of width b_1 is contributing almost 80% or greater discharge for any y_2 on its upstream. Hence except middle step, remaining all steps (2nd to 11th) are joined by a smooth curve to obtain section of 'designed weir'.

Development of equation for smooth curve joining 10 steps (2nd step to 11th step)

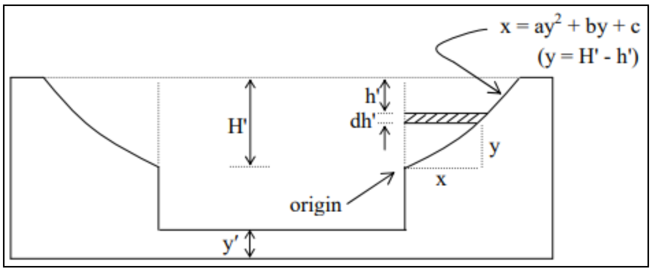

Fig 5: Schematic of designed weir where 2nd to 11th steps is connected by a smooth curve

The weir is required to be designed as stepped weir in the initial stage. Then the centers of all treads (from 2nd step to 11th step) are to be joined by a smooth curved surface. Then by using a method of least square curve fitting, an equation of this curve can be obtained in the form shown in Fig. 5.
With reference to Fig. 5, the total discharge Q for the free flow condition can be given as follows.
Let the total head above origin is H'. Consider an elementary strip of thickness dh' at depth h' from the weir top. Thus, the discharge passing through this elementary strip is given by

$$dQ = C_d\, dh' \sqrt{2gh'}$$

$$= C_d \sqrt{2g}\, (a[H' - h']^2 + b[H' - h'] + c)\, h'^{1/2}\, dh'$$

Therefore, the total discharge passing through the side portion of weir Qs is

$$Q_s = \int_0^{H'} dQ = C_d \sqrt{2g} \int_0^{H'} a\,[H'^2 - 2H'h' - h'^2]h'^{1/2} + b[H' - h']h'^{1/2} + c\,h'^{1/2}\, dh' \qquad (3)$$

$$Q_s = C_d \sqrt{2g} \left\{ a\left[H'^2 \frac{h'^{3/2}}{3/2} - 2H' \frac{h'^{5/2}}{5/2} + \frac{h'^{7/2}}{7/2}\right] + b\left[H' \frac{h'^{3/2}}{3/2} - \frac{h'^{5/2}}{5/2}\right] + c\left[\frac{h'^{3/2}}{3/2}\right] \right\}_0^{H'}$$

$$Q_s = C_d \sqrt{2g} \left\{ a\left[\frac{2}{3}H'^{7/2} - \frac{4}{5}H'^{7/2} + \frac{2}{7}H'^{7/2}\right] + b\left[\frac{2}{3}H'^{5/2} - \frac{2}{5}H'^{5/2}\right] + c\left[\frac{2}{3}H'^{3/2}\right] \right\}$$

$$Q_s = C_d \sqrt{2g} \left\{ a\left[\frac{16}{105}H'^{7/2}\right] + b\left[\frac{4}{15}H'^{5/2}\right] + c\left[\frac{2}{3}H'^{3/2}\right] \right\}$$

Thus, total discharge passing through weir for any head is given by

$$Q = 2\,Q_s + Q_r \qquad (7)$$

Where, Q_r = discharge passing through the middle rectangular portion, and is given by

$$Q_r = \frac{2}{3} C_d\, b_1 \sqrt{2g}\, h_r^{3/2} \qquad (8)$$

Where, b_1 = width of middle rectangular weir portion and h_r = head over rectangular weir crest

Fig 6 shows photographs of 3 weirs wherein 2nd to 11th steps are joined by a smooth curve. In case of broad crested weir, instead of a curved line, a curved surface can be provided.

Fig 6: Photograph of designed weir sections for horizontal apron

Selection of appropriate C_{DM} for submerged flow condition on sloping apron

The procedure adopted to determine C_{dm} for submerged flow conditions on sloping apron is similar to that for horizontal apron. In case of sloping apron, an additional force – i.e. weight component of water, acts in the direction of flow. Therefore hydraulic jump has tendency to move downstream. This factor has to be considered while determining C_{dm}. To arrest hydraulic jump inside basin, it is necessary to increase C_{dm} as compared to corresponding submergence condition on horizontal apron. Based on this logic, ten designed weir sections are designed with modified discharge coefficients (C_{dm}) ranging from 0.6 to 1.1 at an interval of 0.05. The geometries of designed weirs with different C_{dm} values are given in Tables- 3, and 4. Then, by performing experiments for three different slopes, the relation between S_r and C_{dm} is established.

Table 3: Designed weir Geometries for three different submergence ratios on Sloping Apron (Slope 1 in 200, y' = 0.015m)

y_2 m	Widths of steps b m (for S_r = 0.10) (i.e. C_{dm} = 0.8)	Widths of steps b m (for S_r = 0.55) (i.e. C_{dm} = 0.75)	Widths of steps b m (for S_r = 0.70) (i.e. C_{dm} = 0.7)
0.0605	0.0872	0.0930	0.0996
0.0714	0.1041	0.1110	0.1189
0.0807	0.1140	0.1216	0.1302
0.0889	0.1222	0.1303	0.1396
0.0965	0.1292	0.1379	0.1477
0.1034	0.1356	0.1446	0.1550
0.1098	0.1414	0.1508	0.1616
0.1159	0.1467	0.1565	0.1677
0.1216	0.1518	0.1619	0.1735
0.1270	0.1565	0.1669	0.1789
0.1322	0.1610	0.1717	0.1840

Table 4: Designed weir Geometries for three different submergence ratios on Sloping Apron (Slope 1 in 100, y' = 0.015m)

y_2 m	Widths of steps b m (for S_r = 0.10) (i.e. C_{dm} = 0.90)	Widths of steps b m (for S_r = 0.50) (i.e. C_{dm} = 0.90)	Widths of steps b m (for S_r = 0.65) (i.e. C_{dm} = 0.85)
0.0605	0.0777	0.0777	0.0820
0.0714	0.0925	0.0925	0.0979
0.0807	0.1013	0.1013	0.1073
0.0889	0.1086	0.1086	0.1150
0.0965	0.1149	0.1149	0.1216
0.1034	0.1205	0.1205	0.1276
0.1098	0.1257	0.1257	0.1331
0.1159	0.1304	0.1304	0.1381
0.1216	0.1349	0.1349	0.1429
0.1270	0.1391	0.1391	0.1473
0.1322	0.1431	0.1431	0.1515

Conclusion

The geometry of a rectangular built weir is generated using a computerised method and a mathematical procedure. Evidence from experiments shows that average Sr and Cdm are related. A way to determine y' is given. To validate Fluent, a computer model is used in conjunction with data from the lab. An empirical validation of the intended weir's performance was achieved via a pilot scale model study by restricting the location of the hydraulic jump at the spillway's base for a variety of discharges (Qmin-Qmax, Fr1 >4.5, and defined range of Sr). In conclusion, the thesis presents an innovative hydraulic jump-based stilling basin design for tail water insufficiency. A rectangular broad crested built weir is a universal method that addresses the most critical and notorious factor, tail water depth.

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