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# The Art of Physical Hydraulic Modeling and Its Impact on the Water Resources of Pakistan

*Muhammad Salik Javaid and Muhammad Zeshan Khalil*

## Abstract

Before any major hydraulic engineering project is undertaken for planning, designing, construction, or revamping and rehabilitation some kind of model study is but a necessity. Depending upon the time, resources and, significance of the project, the study could be done only on the paper and computer screen using some graphical, analytical or, statistical software and tools, or it could be combined with the more expensive and time consuming physical model study also. This chapter focuses on the question as to why the physical modeling should be reintroduced into engineering practice because of the modern techniques and systems now available for construction, operation and, data analysis of these physical models.

**Keywords:** hydraulic modeling, physical modeling, hydrological modeling, model, prototype, similitude, hydraulic research, Nandipur, barrage, weir, spillway, water resources

## 1. Introduction

The study of physical hydraulic models plays a role which is vital in the planning and designing of almost all hydraulic and hydrologic structures. May it be the stilling basins, spillways of barrages, river training works, hydraulic siphons, or even simple bridges, they are generally designed, evaluated, refined, and improved on the basis of physical hydraulic model studies. Physical model studies are comparatively expensive, costly, consume lots of time and resources to build and operate, and require technical labor and expertise in developing and testing the model. The selection of appropriate scale ratios between prototype and model plays a very significant and imperative role for the reliability and rationality of the results obtained.

Researchers and engineers working in the field, face a real challenge once they have to finalize on the basis of physical and/or numerical models, the rehabilitation and modernization works for any already constructed and operational hydraulic structure. The success of any rehabilitation work depends upon the precise and accurate identification of hydraulic and hydrologic problems on the prototype structure, because any failure may lead to partial or complete wastage of huge investments.

## 2. Hydraulic modeling basics

The laws of similitude enable a researcher to predict the likely performance of prototype hydraulic structures from tests made with far less expensive models. We need not use the same fluid for the model as the prototype. We may obtain valuable results at a minimum cost from the tests conducted on the small scale hydraulic models. Any textbook on hydraulic physical modeling will tell us that the following similarities have to be ensured between the model and the prototype hydraulic structure [1, 2].

### 2.1 Geometric similarity

Model and prototype should have identical shapes but differ only in size as per the defined scale ratio. This would ensure geometrically similar flows. Under certain conditions, distorted models are resorted to by having different scale ratios for the lateral, longitudinal, and vertical directions, but then the same has to be incorporated during the interpretation of results.

### 2.2 Kinematic similarity

Ratios of the velocities on all corresponding points on the model and prototype hydraulic structure should be the same to ensure the same kinematics of flow.

### 2.3 Dynamic similarity

The quantum and direction of all forces acting on the corresponding points on the model and prototype should be in the same ratio, to ensure the same dynamics of the flow. Dynamic similarity can also be ensured by ensuring similarity of the combination of forces, by following the Froude Law, Reynolds Law, Mach Law, etc., for modeling.

## 3. Physical hydraulic modeling

Physical modeling of hydraulic structures has been in use since the times of Leonardo Da Vinci. However, since then this art and science have gone manifold changes, developments, and positive improvements. Such models provide a visual insight into the hydraulic phenomena of water and fluid flows. These models also provide technical flow data through the elaborate system of instrumentation provided. The data and flow visuals can be recorded for future reference, computations, training materials, and records.

The role of hydrological modeling has been well described in [3], wherein the authors reiterate that hydrological models are in fact basic, theoretical, and physical representations of the hydrologic cycle, and these are often used for the understanding and prediction of hydrological processes. They categorize the hydrological models as (a) models which are based on data collection, and (b) black-box models which are based on process description.

Because of the importance and special role of physical hydraulic modeling, various renowned organizations have developed their physical hydraulic research centers. The most common and well-known are the Waterways Experiment Station (WES) of the US Army Corps of Engineers and Hydraulic Research Station (HRS) of Punjab Irrigation Department, Pakistan.

### 3.1 Waterways Experiment Station (WES)

The US Army Corps of Engineers Waterways Experiment Station (WES) was created in 1929 to provide support for the vast flood control plan for the entire lower Mississippi valley after the tragedy of the 1927 most horrific river flood. The WES laboratory complex located at Vicksburg, Mississippi is now the principle research, testing, and development facility, which supports studies in many other fields in addition to its primary field of hydraulic engineering. WES provides services for training, and technical assistance, research, and also software development, which reflects the state-of-the-art expertise of WES in hydrologic engineering and closely associated fields of planning analysis. In its research and development work, WES uses more application of model experiments employing the principles of hydraulics. WES has made a significant contribution through the publication and distribution of its research reports.

### 3.2 Hydraulic Research Station (HRS)

Hydraulic Research Station, located at Nandipur near Gujranwala, in Pakistan is one of the largest research laboratories in the world. This field research station was established in 1926 and is under the administrative control of the Irrigation Research Institute, Lahore being its field station. The Nandipur station has 40 hectares of land divided into 22 research bays commonly called as research trays. Through a small irrigation channel, the water availability of 15 cumecs and a gravity head of 4 meters is provided, however for higher heads pumping facility is also available. The Nandipur Hydraulic Research Station meets the requirement of the study of numerous problems that are related to planning, operation, and management of water resources. Physical models for almost all the major irrigation and hydraulic structures now present in the country have been run, tested, and optimized at this station.

Hydraulic Research Station at Nandipur has carried out model studies of almost all major hydraulic engineering projects undertaken in Pakistan and India in the pre-partition as well as the post-partition era. The major projects of Mangla Dam and Tarbela Dam which were constructed as part of the Indus Basin Treaty were also modeled in this facility. Many other barrages, weirs, link canals, and river training works have been modeled and approved prior to the finalization of their designs. A sample of the physical hydraulic modeling projects undertaken by the Hydraulic Research Station is displayed in **Figures 1** and **2**.



**Figure 1.**  
*Flow from Flip Bucket Energy Dissipater.*



**Figure 2.**  
*Model of a Typical Barrage.*

In the recent past, the rationality of the massive hydraulic structure of Jinnah Barrage [4, 5] was questioned as a model study indicated that at existing conditions of water levels the formed hydraulic jump was located on the glacis only up to a discharge of 400,000 cusecs. The hydraulic performance of the barrage, under-sluices, silt excluders, and also the subsidiary weir was yet not tested at higher discharges. Mahboob [6, 7] reviewed the design of Kalabagh Barrage and he found it acceptable only after the physical hydraulic model study because the hydraulic modeling study for energy dissipation under the conditions of existing water levels pointed out that hydraulic jump over the horizontal floor was repelled by the excessive lowering of the channel bed at the downstream (retrogression) (**Figure 3**).



**Figure 3.**  
*Model Study of Taunsa Hydro Power Project.*

#### 4. Physical modeling: a case study

The hydraulic modeling study cited here targets to examine sedimentation aspects of two cascade reservoirs on Poonch River; with the help of physical modeling and numerical simulation. A physical model of Poonch River was prepared at Nandipur Research Institute to study the sediment transport behavior [8]. After the base test, the model was used to get data for various scenarios of sediment flushing in the cascade reservoir system. The River geometry, riverbanks, hydraulic structures, cross-sections, and other physical attributes of the river were prepared from a topographic



**Figure 4.**  
*Model Study of Poonch River Sedimentation Project.*



**Figure 5.**  
*Model Study of Poonch River Sedimentation Project.*

survey using AutoCAD. These files were used in HEC-RAS and BASEMENT for simulations (**Figure 4**).

Delta profile and flushing were modeled by HEC-RAS 5.0. The simulation showed that the life of the un-sluiced Gulpur HPP is about 14–15 years and that of Rajdhani is about 35 years. To enhance the life of the project, annually 4–5 days are required for flushing with an optimized discharge of about 250 m<sup>3</sup>/s. Model verification was performed by calculating the bed topography and flushing efficiency. The results obtained through the model were consistent with bed changes, demonstrating its suitability for the regeneration of regression channels and lateral erosion (**Figure 5**).

## 5. Revival of the vanishing art

Other techniques in addition to physical hydraulic modeling available to a researcher are mathematical modeling, statistical modeling, and numerical modeling. With the advent of modern computers having speedy and fast processors, massive data storage, better data management software, and intelligent computational techniques the statistical modeling and numerical modeling have become the favorites of every researcher and engineer. The cutting edge graphics cards and attractive presentation techniques have also added to the magnetism of such indoor modeling. However, despite all this, the value and importance of physical hydraulic modeling cannot be overshadowed by these. The natural intricacies, physical behavior, the kinematics and dynamics of all fluids and especially large mass flows of water can only be studied through physical modeling.

With the innovation of new materials of construction including the nano-materials, the physical hydraulic modeling has been revived. Now very intricate designs can be created and manufactured using new and modern materials. The same is true for hybrid and very strong epoxies and sealing materials which now help in making watertight models. Fabrication of models and their miniature parts has also been revolutionized by laser cutting, computerized numerical machines that can make precision model parts.

Revolution in measuring instruments for all hydraulic parameters has also provided a quantum jump to physical hydraulic modeling. Doppler velocimetry, very sensitive and accurate probes and pressure transducers, laser leveling gauges, and other such instrumentation can now be used to obtain and collect very sophisticated data for physical hydraulic models.

The latest techniques in flow visualization have done wonders in fluid mechanics and hydraulic modeling. Modern electronics and advancement in graphics, optics, and sensors has revitalized the hydraulic modeling and made it an advanced and modern field of science and technology.

On the other hand, the models based on process description also called deterministic models are rather complicated as compared to the stochastic hydrological models representing surface runoff, channel flow, subsurface flow, and evapotranspiration. Such models cannot be physically modeled, and therefore these have to be computer modeled [3].

## 6. Recommendations and conclusion

The art, science, and technique of planning, construction, and operation of physical hydraulic modeling are losing the race against numerical and computer modeling. However, there is a dire need that due to its very special place in research

and investigation, this modeling technique should remain in vogue. For this very purpose its education, teaching, and engineering practice may be included in the curricula of various universities, colleges, and other technical training institutes.

For very important and significant hydraulic structures, the failure of which cannot be afforded due to various reasons, it may be made mandatory that physical hydraulic modeling is carried out prior to the finalization of designs of construction and rehabilitation.

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