Development and Evaluation of a Laboratory-Scale Hydrological Apparatus for Simulating Soil Erosion and Groundwater Processes

Fayaz Ahmad [1], Zainab Asad [1], Muhammad Haris [1], Huda Shafqat [1], Taj Ali Khan [1*]

Abstract

Background: The effective management of water infiltration, runoff, and soil degradation remains a critical challenge in water resource planning and environmental management. With increasing global water management concerns, tools such as rainfall simulators and erosion and sediment control (ESC) measures have become essential in studying hydrological processes. These tools aid in understanding the impact of natural phenomena and human activities on water systems, soil erosion, and sediment transport. Methods: This study utilized a custom-built hydrological apparatus to simulate and monitor rainfall, runoff, and groundwater processes under controlled laboratory conditions. The apparatus featured adjustable components such as a sand tank, rainfall simulation system, and supporting frame to replicate varied hydrological scenarios. Experiments focused on surface water flow, groundwater abstraction, and soil erosion by simulating real-world conditions like rainfall intensity, soil composition, and slope variations. Data on water infiltration, erosion, and sediment transport were collected for analysis. Results: The apparatus successfully replicated diverse hydrological conditions, providing key insights into soil erosion, water infiltration, and runoff patterns. It demonstrated the effects of slope and soil composition on water retention, with clay soils showing the highest water retention (7.28 L/min) and sandy soils exhibiting rapid drainage (0.16 L/min). Simulated rainfall enabled the creation of storm hydrographs and detailed monitoring of overland flow and erosion. Groundwater experiments, using Darcy's law, revealed how varying conditions affected subsurface flow rates and water table fluctuations. Conclusion: The study demonstrated that controlled laboratory simulations can provide high-quality data on hydrological processes, complementing field studies and enhancing the understanding of water management systems.

Keywords: Hydrological Apparatus, Soil Erosion Simulation, Groundwater Flow, Rainfall Simulation, Water Management

Significance | This apparatus advances understanding of soil erosion and groundwater flow, crucial for effective water management and environmental planning.

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Introduction

Water management, particularly the quantification of water infiltration, runoff, and soil degradation, has long been a critical challenge for engineers, environmental planners, and hydrologists. These processes play a vital role in water resources management, environmental planning, and wastewater conveyance systems. As global water management and sediment transport problems continue to intensify, there is a growing demand for innovative and creative methods to better understand, evaluate, and manage the available water resources. This has led to a deeper understanding of

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natural processes like runoff and sediment generation, alongside an assessment of human activities' influence on water systems. Achieving such insight requires continuous monitoring and data collection (Zokaib & Gh, 2012). To address this growing need, erosion and sediment control (ESC) measures have emerged as vital tools in mitigating water and soil management challenges. These measures range from soil stabilization techniques such as mulch (including vegetation, erosion control blankets, and hydro mulch), to runoff control measures like inlet protection, ditch checks, and turf reinforcement mats. Sediment control strategies, including sediment basins and silt fences, also play a crucial role. Given the increasing use of these practices, it has become essential for researchers, practitioners, contractors, and regulatory agencies to understand the field performance of various ESC measures, as well as their appropriate applications. The implementation of standardized small-scale testing methods over the years has facilitated such understanding.

Since the mid-20th century, various hydrological instruments and rainfall simulators have been employed to simulate and study these processes. Notably, rainfall simulators have enabled the study of runoff, soil erosion, sediment transport, and groundwater flow in controlled environments. Simulated rainfall through pressurized systems allows for the design of smaller, more portable simulators, which in turn have provided researchers with a tool that can withstand environmental conditions during outdoor studies (Blanquies et al., 2003; Elbasit et al., 2015; Miller, 1987; Horne, 2017).

One notable apparatus used in such studies is the hydrological apparatus, an independent, floor-standing device with a water reservoir tank, soil tank, and overhead spray nozzles designed to simulate rainfall. This apparatus has become an essential tool for evaluating hydrological processes such as soil erosion, infiltration, groundwater flow, and water abstraction. By simulating rainfall through nozzles or sprinkler heads, researchers can produce rain-like drops with a pressurized system. This design ensures that raindrops reach terminal velocity faster, thus allowing for shorter and more portable simulators. The hydrological apparatus, with its ability to simulate three-dimensional groundwater flow and associated water levels, has greatly facilitated small-scale practical demonstrations and research.

Soil bed symmetry plays a critical role in both irrigation and construction applications. In irrigation, soil bed formation significantly impacts water transport, determining the proper supply of water to crops. Symmetry in soil combinations ensures the efficient supply of water without unnecessary wastage or absorption. In developing countries, where agriculture dominates the economy, increased pressure on land and water resources due to population growth has led to significant water utilization challenges. Under these conditions, field experiments using apparatus like the hydrological simulator are essential for improving our understanding of the interrelationships within hydrological processes (Hanif et al., 2019).

Engineers often focus on urban and irrigation water supply, land drainage, the impact of excavation works on groundwater, and the drainage of lakes and polders. However, geologists and geographers are also frequently confronted with challenges related to hydrological processes, such as soil erosion caused by surface and subsurface water flow. For researchers working in these fields, the hydrological apparatus offers a significant advantage: it provides control over experimental conditions, allowing experiments to be conducted without having to wait for natural rainfall or groundwater events (Mutchler & Hermsmeier, 1965).

Numerous studies have made significant contributions to the development and understanding of hydrological processes using rainfall simulators and hydrological apparatuses. For example, Amadu and Miadonye (2019) investigated the absolute permeability of a model sand-containing water layer using a hydraulic flow model. Their research, conducted under laboratory conditions with ambient dynamic viscosity and density, provided valuable insights into the behavior of groundwater and hydrocarbon flow in porous media. The hydraulic model used in their study, HM 167, enabled the creation of various hydraulic or petrophysical models based on different sand grain sizes. The ability to simulate groundwater flow under controlled conditions resulted in groundbreaking experimental data, offering a better understanding of radial diffusion equations that describe such processes.

In another study, Hanif et al. (2019) examined the effects of soil bed formations under severe rainfall conditions using an advanced hydrological apparatus. Their study primarily focused on water retention and discharge rates across various soil types and combinations at different slopes. They found that soil type ST-1 (100% clay) retained the largest quantity of water (7.28 L/min), making it ideal for irrigation, while soil type ST-2 (100% sand) drained water more quickly (0.16 L/min), making it more suitable for construction purposes. Furthermore, soil slope significantly influenced water resistance, with higher slopes contributing to increased water retention in clay soils. These findings underscore the importance of soil composition and slope in optimizing soil bed formations for both construction and irrigation.

The use of artificial neural networks (ANNs) in Hanif et al.'s (2019) study further demonstrated the potential of advanced computational techniques in predicting the behavior of hydrological systems. By integrating various parameters into their models, the researchers were able to better understand the complex interrelationships between soil types, slopes, and water flow. Their study represents a valuable step forward in the development of more effective ESC measures, with practical applications in both agriculture and engineering.

The quantification of water infiltration, runoff, and soil degradation remains a critical challenge in water resources management and environmental planning. However, the use of ESC measures, rainfall simulators, and hydrological apparatuses has significantly advanced our understanding of these processes. By simulating natural events in controlled environments, researchers have been able to gather valuable data on soil erosion, sediment transport, and groundwater flow. As water management challenges continue to grow, the development of innovative methods and technologies will be essential in ensuring the sustainable use of our planet's most vital resource.

Material and Methods

This study utilized a custom-designed hydrological apparatus for controlled laboratory simulations of hydraulic processes, including rainfall runoff, groundwater abstraction, and river morphology development. The apparatus allowed for the replication of real-world hydrological cycles, offering valuable insights into water-soil interactions, erosion, and water management systems. The setup enabled precise simulation of hydrological phenomena without the need for complex external infrastructure, thus providing a controlled environment for conducting varied hydraulic experiments.

Design Structure and Materials

The hydrological apparatus consisted of several integral components: a supporting frame, various tanks, a water pump, and a rainfall simulation system. Each of these components was designed to replicate key elements of hydrological cycles.

Supporting Frame

The supporting frame served as the structural foundation for the apparatus, designed to withstand the system's weight and allow for slope and height adjustments, critical for simulating different terrains and rainfall scenarios. The frame was constructed using:

• 18-gauge, 25 × 25 mm, 6-meter pipes (6 kg/pipe) for the rainfall simulation support.

• 18-gauge, 38 × 38 mm, 6-meter pipes (8 kg/pipe) for the primary structural framework. This robust framework ensured stability and flexibility during various experimental setups.

Tank Structures and Accessories

Sand Tank

The sand tank was central to experiments involving soil infiltration, runoff, and groundwater flow. Constructed with:

• 22-gauge carbon steel sheets

• 1” GI union pipe fittings and tees

• Piezometer tubes to measure water pressure

• 1” plastic pipes simulating wells

• 1” PPR pipes for water flow channels. The sand tank facilitated varied soil configurations, enabling experiments on the effects of soil type on hydrological processes.

Water Supply and Receiving Tanks

Two tanks, serving as inlet and outlet reservoirs, were located at either end of the apparatus, separated by a weir with porous portholes. These tanks, measuring 20 × 30 × 25 cm, controlled water inflow and outflow, ensuring accurate simulations of surface runoff and infiltration. The tanks were constructed using:

• 22-gauge carbon steel sheets

• 1” bushings for secure connections.

Reservoir Tank

A reservoir tank with dimensions of 50 × 70 × 30 cm (capacity of 105 liters) provided a continuous water supply, ensuring the uninterrupted function of the apparatus. The tank was made from:

• 22-gauge carbon steel sheets

• 1” bushings for connections to the water pump.

Water Pump and Accessories

The apparatus employed a ½ horsepower water pump with a discharge capacity of 36 liters per minute to supply controlled volumes of water, simulating rainfall, groundwater flow, and surface runoff. The pump system included:

• 1” GI cross tees and unions

• 1” nozzles to direct water flow during experiments.

Rainfall Simulation System

The rainfall simulation system was a critical component designed to replicate natural rainfall with precise control over drop size, distribution, and intensity. The system consisted of:

• Head nozzles for spraying water uniformly

• Control valves to regulate water flow

• ½” GI pipes, tees, elbows, and cross tees for the water supply network. This system allowed for the controlled study of rainfall's impact on soil erosion, runoff generation, and overland flow dynamics.

Experimental System

Two main experimental systems were developed to study surface water flow and groundwater flow.

Study of Surface Water Flow

Surface water flow was examined using the apparatus as a rainfall simulator, replicating real-life rainfall events under different conditions.

Rainfall Simulation and Runoff

Rainfall simulation was conducted by adjusting the nozzle settings to control drop size and intensity. Drop size ranged between 2-3 mm, with distribution calculated using the equation:

Dm=2.23I0.182D_m = 2.23 I^{0.182}Dm=2.23I0.182

where DmD_mDm is the median drop diameter (mm) and III is the precipitation intensity (in./hr). The apparatus simulated various rainfall intensities, replicating real-world conditions.

Rainfall-Runoff Experiments

The rainfall simulator allowed for the study of storm hydrographs, which capture the relationship between rainfall and runoff. These experiments involved creating artificial rain over a sloped sand surface and measuring runoff over time, generating hydrographs to analyze the time-lag between rainfall and runoff, and the effect of soil saturation.

Overland Flow and Erosion

Overland flow was studied by adjusting the slope of the sand tank (typically between 3.5% and 4.5%) and simulating rainfall events of varying intensity. The generated overland flow was observed for surface erosion patterns, drainage system development, and the initiation of bedload motion.

Study of Groundwater Flow

Groundwater flow experiments utilized the apparatus as an aquifer model, simulating well abstraction and subsurface water movement.

Groundwater Abstraction and Darcy's Law

The apparatus simulated groundwater flow through a tank filled with sand, where water abstraction from wells affected the water table and flow patterns. Darcy's law was applied to analyze groundwater movement, expressed by the equation:

V=kdhdlV = k \frac{dh}{dl}V=kdldh

where VVV is the flow rate, kkk is the permeability coefficient, and dh/dldh/dldh/dl is the hydraulic gradient. This provided insights into subsurface water behavior under varying conditions of well pumping and recharge.

Impact on Water Table and Streamflow

The study of groundwater abstraction focused on its impact on the water table and nearby streamflows. By adjusting pumping rates and monitoring water table fluctuations, the apparatus demonstrated how groundwater depletion affects surface water availability, providing a model for water resource management in real-world scenarios.

The hydrological apparatus employed in this study offers a reliable and versatile platform for simulating various hydrological processes. Through experiments on rainfall runoff, groundwater abstraction, and surface erosion, the apparatus provided valuable data on the interactions between soil and water under controlled conditions. This setup allows researchers to analyze the hydrological cycle's impact on natural and engineered environments, with applications in environmental planning, water resource management, and sustainable engineering practices.

Results

The study successfully designed and constructed a laboratory-scale rainfall and hydrological apparatus to simulate soil erosion and groundwater processes, which offers detailed control over variables such as water flow, spray intensity, and slope inclination. The apparatus was assembled with a sturdy metal frame, a sand tank for erosion and infiltration experiments, inlet and outlet tanks, and a system of spray nozzles for rainfall simulation (Figure 1).

Frame Structure

The adjustable metal frame provided the primary support for the entire system, enabling the elevation of the sand tank using a screw mechanism. This allowed for the simulation of different terrain slopes. The roof of the frame was designed to adjust the height of the spray nozzles, ensuring that rainfall intensity and coverage could be optimized for various experimental needs.

Sand Tank

The shallow sand tank, fabricated from stainless steel for corrosion resistance, formed the core of the experimental setup. As illustrated in Figure 2, the tank included an array of tapping points connected to a multi-tube manometer for measuring the phreatic surface (water table). The integration of cylindrical wells, covered with mesh to prevent sand loss, allowed for controlled groundwater abstraction experiments without affecting surface flow. The system's valves and pipework beneath the tank efficiently managed water drainage, supporting both surface and subsurface flow experiments.

Water Supply System

The water supply system, consisting of a reservoir, a centrifugal pump, and flow control mechanisms, supplied water to the apparatus through quick-release connectors. These connectors allowed water to be fed into different components, including the spray nozzles, inlet tank, and sand tank. The flow control valve and rotameter, (Rotameter is a device used to measure the flow rate. It is connected with the pipe which is supplying water to spray head nozzles to measure the intensity of rainfall), enabled precise regulation of water flow, enhancing the accuracy of simulations involving rainfall runoff and infiltration.

Outlet Collecting Tank

The outlet tank, located at the far end of the sand tank, collected water and sediment exiting via a weir structure (Figure 9). This setup facilitated the measurement of water discharge and sediment load, allowing for a comprehensive analysis of soil erosion and water flow dynamics.

Inlet Tank and Rectangular Weir

The river inlet tank simulated upstream river flow across the sand tank surface, utilizing a rectangular weir structure for discharge measurement (Figure x). The discharge coefficient CeC_eCe and notch width bbb were determined using ISO standards, and the calculated discharge rate of 0.1725 cubic feet per second was derived using the equation:

Q=Ce(b+kb)(h+0.003)2Q = C_e (b + k_b)(h + 0.003)^2Q=Ce(b+kb)(h+0.003)2 (Figure 3 to 8).

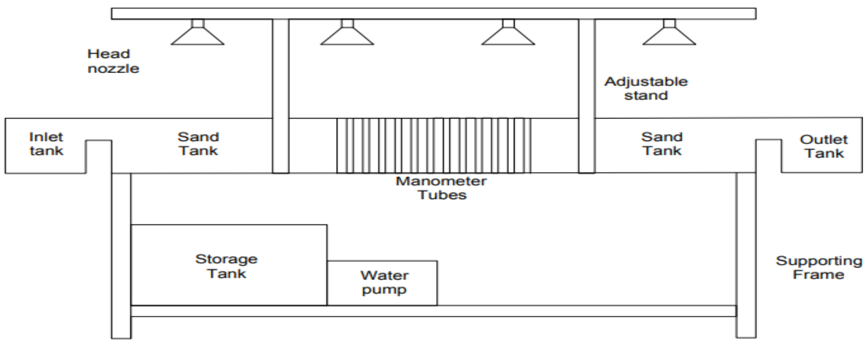

Figure 1. Schematic diagram of the rainfall and hydrological apparatus

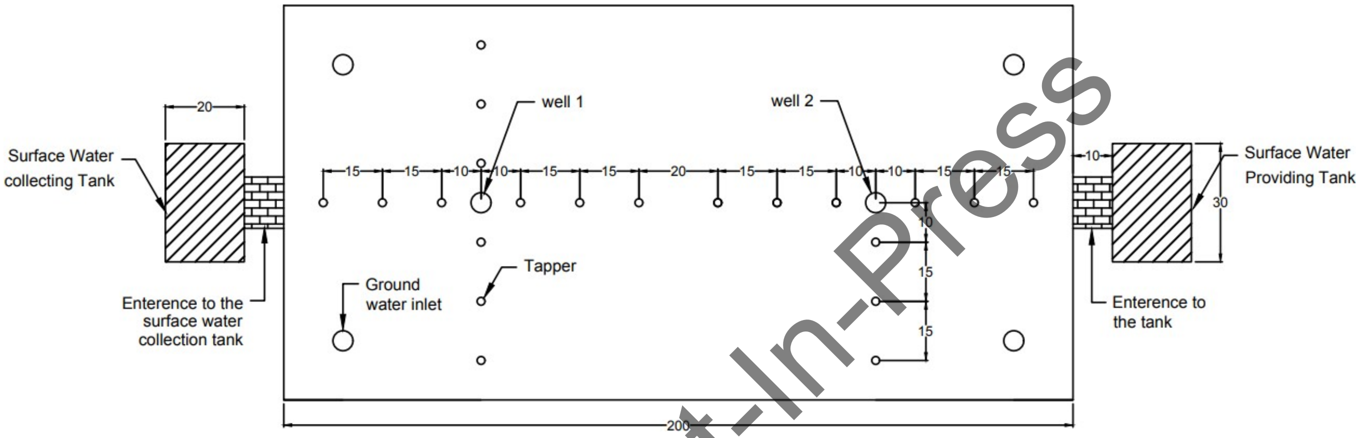

Figure 2. Top view of sand and arrangement of tappings

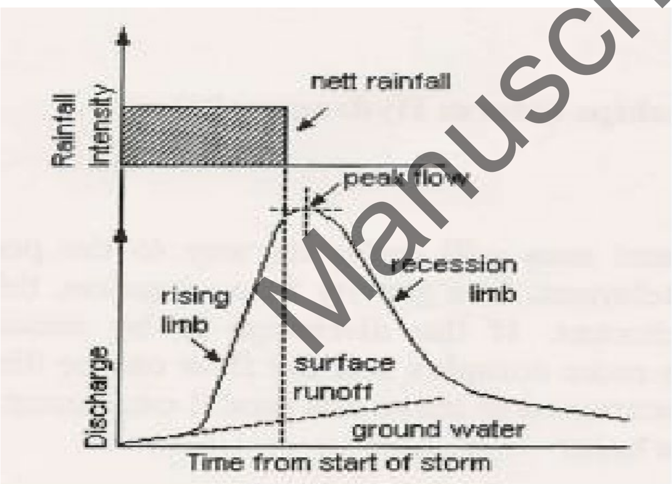

Figure 3. Rainfall-Runoff Hydrograph for a Storm of Shorter Duration

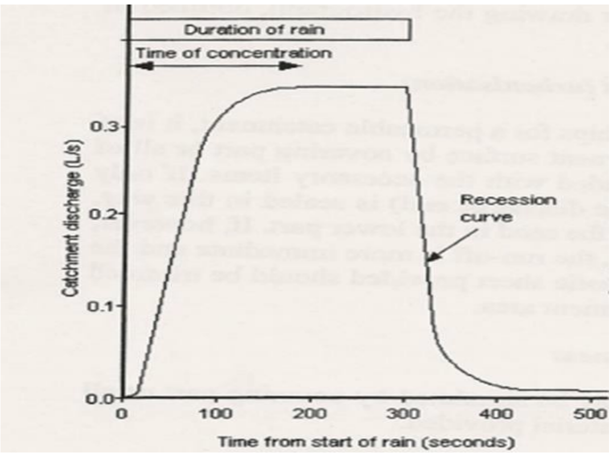

Figure 4. Rain duration greater than the time of concentration for catchment

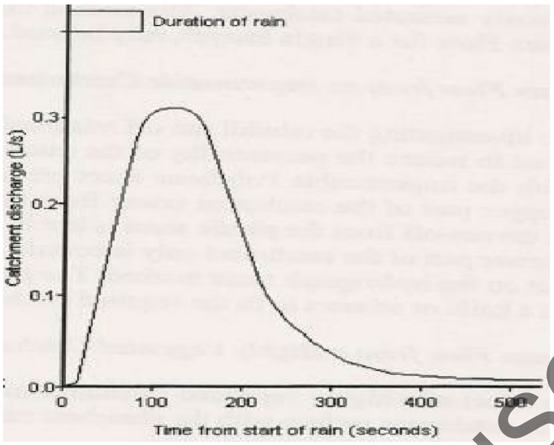

Figure 5. Rain duration less than the time of concentration for catchment

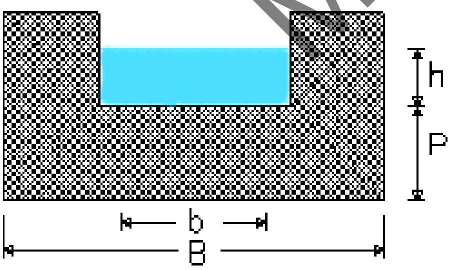

Figure 6. Design and Components of the Laboratory-Scale Rainfall and Hydrological Apparatus

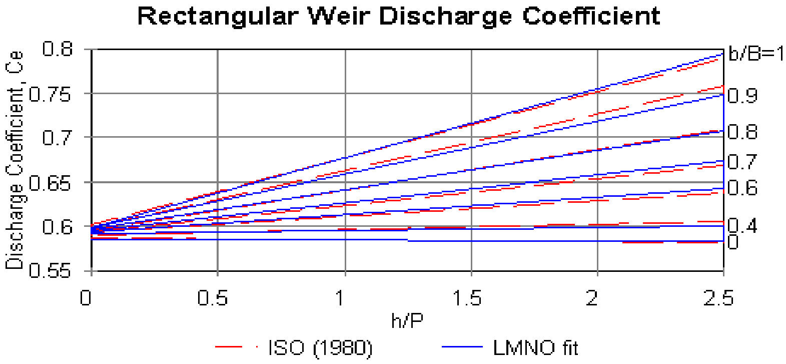

Figure 7. Graph to find Discharge Coefficient

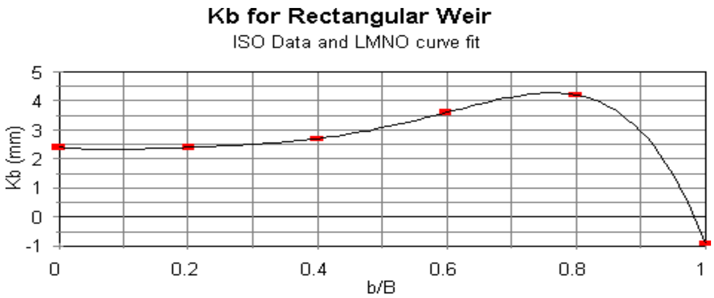

Figure 8. Graph to find Kb using b/B ratio

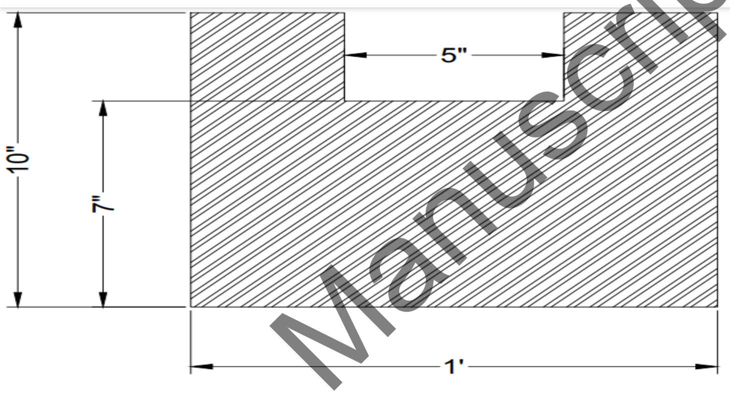

Figure 9. Rectangular weir structure

This allowed for accurate modeling of water inflow and the study of its impact on surface runoff and infiltration.

Spray Nozzles, Manometer Tubes, and Rotameter

The rainfall simulation system utilized eight spray nozzles mounted on the frame, delivering controlled rainfall to the sand tank. The height of the nozzles was adjustable, allowing for experiments at varying rainfall intensities. Manometer tubes connected to tapping points in the sand tank provided real-time data on water flow direction and water table levels. The six tubes on either side of the frame, along with the centerline tube, provided precise measurements of hydraulic gradients across the tank (Figure 5).

System Performance and Data Collection

The overall apparatus performed as expected, demonstrating the capability to replicate rainfall events, soil erosion, and groundwater flow under controlled conditions. Data collected from the multi-tube manometer and outlet collecting tank provided critical insights into water infiltration rates, surface runoff patterns, and sediment transport. The calculated discharge rate from the rectangular weir (Figure 9) validated the system's precision in replicating real-world hydrological conditions.

The design and construction of the hydrological apparatus allowed for a wide range of experiments on plot-scale hydrological processes, offering accurate measurements of water flow, sediment displacement, and soil erosion under varied conditions. This system serves as a valuable tool for future studies on hydrological dynamics and erosion control strategies.

Discussion

The development of this laboratory-scale rainfall and hydrological apparatus offers a versatile and effective tool for both teaching and research purposes in hydrology. Its design, which incorporates adjustable components such as the roof, slope, and rainfall intensity, allows for precise simulation of real-world hydrological conditions. This adaptability makes it a valuable alternative to field-based studies, especially in situations where conducting experiments outdoors may be impractical due to environmental constraints, logistical difficulties, or time limitations.

The apparatus provides a controlled environment for studying key hydrogeological processes such as surface runoff, soil erosion, and groundwater flow. Its flexibility in simulating different rainfall intensities and slope angles enhances its ability to replicate various environmental scenarios, thereby ensuring that the results are more applicable to real-world conditions. This versatility, combined with its ease of operation, makes it an effective tool for generating data on runoff and erosion, which are crucial for soil conservation efforts and water quality assessments.

In addition to its utility in surface water studies, the groundwater flow model integrated into the system is designed to facilitate three-dimensional studies of groundwater behavior, making it particularly useful for addressing practical problems such as dewatering during excavation projects. The ability to simulate drawdown tests in a laboratory setting offers a controlled means of estimating the hydraulic conductivity of sand packs or sand filters. This has significant implications for the design of filtration systems, particularly in agricultural and civil engineering applications.

The portability and user-friendly nature of the apparatus make it a practical choice for use in academic settings, where time constraints often limit the scope of experiments. By allowing researchers and students to perform hydrological experiments within a short time frame, the model proves itself as a highly efficient tool for education. Additionally, the apparatus' ability to simulate real-world hydrological phenomena provides an excellent platform for illustrating hydrogeological concepts in classroom demonstrations, bridging the gap between theoretical learning and practical experience.

This apparatus represents an important contribution to both research and education in hydrology, particularly in fields like agriculture, soil science, and environmental engineering. It enables precise experimentation and analysis in a laboratory setting, which can complement and, in some cases, substitute for field studies. The apparatus not only enhances the understanding of water movement, erosion, and soil conservation but also expands the potential for controlled research into groundwater behavior and filtration system design. Its adoption could lead to more reliable and replicable data for researchers, making it a valuable addition to hydrological research and teaching programs.

Conclusion

The laboratory-scale hydrological apparatus developed offers a significant improvement in simulating soil erosion and groundwater processes. By enabling precise control over rainfall intensity, slope, and other variables, the apparatus provides a robust tool for studying various hydrological phenomena in a controlled environment. The adaptability of the system allows for the replication of real-world conditions, which is essential for accurate experimentation and data collection. The results obtained from this apparatus offer valuable insights into water infiltration rates, surface runoff patterns, and sediment transport, which are critical for effective erosion control and water management strategies. Furthermore, the apparatus proves to be a practical alternative to field studies, especially in scenarios where environmental constraints or logistical issues limit outdoor experimentation. Its application extends to both educational and research settings, providing a valuable resource for understanding and managing hydrological processes.

Author contributions

T.A.K. conceptualized the project, developed the methodology. Z.A. conducted formal analysis, and drafted the original writing. M.H. and H.S. contributed to the methodology, conducted investigations, provided resources, visualized the data. F.A. contributed to the reviewing and editing of the writing.

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Competing financial interests

The authors have no conflict of interest.

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