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# Investigation of Hydraulic Characteristics and Fluid Dynamics in Sand Samples from the Osun River in Osogbo, Nigeria

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## ABSTRACT

Understanding the natural flows in porous media with specific hydraulic characteristics is crucial for advancing science and engineering. This study examines the hydraulic properties and fluid dynamics of sand samples collected from eight locations along the Osun River bed at five-meter intervals in November 2023. Significant variations in hydraulic characteristics were identified by comparing the findings with international soil classification standards. The effective grain size ranged from 0.20 mm to 0.32 mm, with most samples between 0.30 mm and 0.31 mm. Sample F had the smallest grain size, indicating finer sand. Flow velocities varied from 1.57 cm/s to 2.41 cm/s, with the highest observed at locations B and E. Flow rates ranged from $1.23 \times 10^2$ $cm^3/s$ to $1.89 \times 10^2$ $cm^3/s$, also highest at B and E. Reynolds numbers ranged from $1.39 \times 10^6$ to $8.58 \times 10^6$, indicating transitions from laminar to turbulent flow. Friction factors ranged from $7.46 \times 10^6$ to $45.85 \times 10^6$, with higher values at location A, indicating greater resistance to flow. Hydraulic gradients ranged from 1.09 to 1.83, and hydraulic conductivities were between $1.14 \times 10^{-2}$ cm/s and $1.43 \times 10^{-2}$ cm/s, with the highest observed at location A. The results align with recent research showing that coarser sands exhibit higher hydraulic conductivities and flow rates, whereas finer sands demonstrate greater resistance. The study underscores the importance of monitoring friction factors, flow velocity, flow rate, and Reynolds numbers to manage potential environmental hazards and water seepage through dams.

## INTRODUCTION

The flow through porous materials is a vital area of study across numerous scientific disciplines, such as environmental science, hydrology, hydraulic engineering, hydrogeology, chemical engineering, and petroleum extraction (Jiang et al., 2020; Karamouz et al., 2020; Konstantinou & Biscontin, 2022). Understanding fluid movement through porous materials is crucial for comprehending various phenomena such as pollutant transport, subsidence due to water shortages, and the crystallization of ores in geothermal wells, which may render them unsuitable for heat extraction. Moreover, the relationship between fluid injection into the subsoil and seismic activity, exemplified by the Rangeley experiment in Colorado, along with the connection between rising water levels in wells and increased seismic activity, are important topics for exploration (Das, 2020; Jerbi et al., 2017; Yu, et al., 2021; Zhang et al., 2020).

Permeability is a key physical characteristic influencing a material's porosity and subsequently determines its ability to allow fluid passage. Soil frequently serves as a filtration medium; thus, understanding of permeability in both homogeneous and heterogeneous media is essential for filter design (Gago et al., 2019; Nishiyama & Yokoyama, 2017; Wang et al., 2022). Porous media, including soil and other permeable materials, are typically modeled as continua characterized by properties such as dimension and porosity (Hommel et al., 2018; Konstantinou & Bisticontin, 2022; Ren et al., 2018). Studies show that permeability is influenced by several factors including particle size, shape, orientation, and surface texture. Alternatively, the continuum method involves averaging velocity and pressure over a volume large enough for accuracy but small enough to be infinitesimal relative to the sample (Erol et al., 2017; Qingrong et al., 2016). However, this method is less effective for flows of substance through large holes or around obstacles.

In essence, Darcy's law can be seen as an outcome of applying average values to the more complex Navier-Stokes equations while focusing on the large-scale behavior of fluids in porous materials. A thorough understanding of fluid flow in porous and heterogeneous materials is crucial for applications such as oil and gas extraction, pollutant dispersion control, and the design of efficient filtration systems. Although the basic principles of creeping fluid flows are well understood, the complex micro-scale structures of these materials make studying fluid flow challenging (Kovalchuk & Hadjistassou, 2019). The interaction between fluid flow and these microstructures influences the macro-scale flow properties, which can be analyzed using computerized X-ray micro-tomography (Ray, 2017).

Understanding fluid movement through porous materials is crucial for various scientific and engineering applications, including environmental management, hydrogeology, and hydraulic engineering. (Konstantinou et al., 2021). Despite extensive studies on permeability and fluid flow in porous media, challenges remain in accurately modeling and predicting flow behavior in heterogeneous materials, particularly in natural river sediments. The authors reiterated further that, the complexity of micro-scale structures in porous media affects macro-scale flow properties, influencing applications such as pollutant transport, groundwater recharge, and filtration efficiency.

In Osun River, Osogbo, Nigeria, sand deposits play a significant role in groundwater movement, sediment transport, and filtration processes. However, limited research has been conducted to characterize the hydraulic properties and fluid dynamics of these sand samples, leading to gaps in knowledge about their permeability, porosity, and overall impact on water movement. This study aims to address this gap by investigating the hydraulic characteristics of sand samples from the Osun River, providing insights into their suitability for filtration, seepage control, and water resource management.

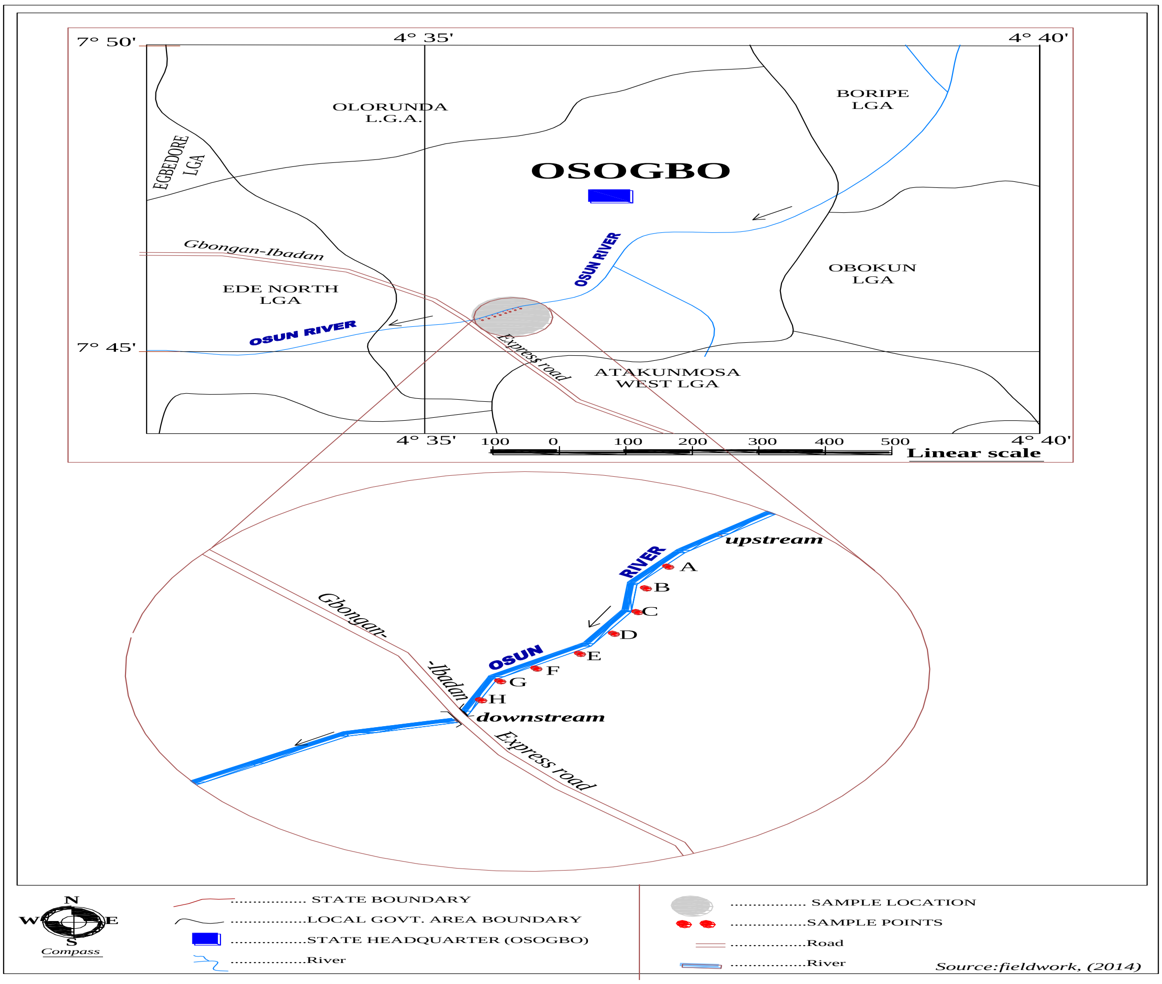
## METHODS

### Study Area Overview

Osogbo, the capital of Osun State, Nigeria, became the state capital in 1991 after the reorganization of Old Oyo State. Located about 95 km northeast of Ibadan (7°00' - 8°02' N, 4°02' - 5°01' E), it covers approximately 140 km² at an elevation of 366 m (Oladipo, 2021). The city has a population density of 350–500 people per square meter and experiences a Guinea Savannah climate with annual rainfall of 1100–1500 mm. Its population grew from 106,386 in 1991 to 155,507 in 2006 (Adeolu, 2022).

### Method of Sampling

Soil samples were collected from eight distinct locations along the Osun River bed in Osogbo with sampling points spaced hundred (100) meters apart (see Fig. 1). The equipment used for testing included a falling head permeameter, a weighing balance, a thermometer, a stopwatch, a burette, a tripod stand, a funnel, and a porous stone. The river sand samples were labeled A through H for identification purposes. Furthermore, water for the study was extracted from a hand-dug well adjacent to the Geotechnical Laboratory at the Federal University of Technology in Akure. Upon collection, the river sand samples were immediately transported to the laboratory, where moisture content tests were conducted according to BS 1377 standards (Ogenleye & Adeleye, 2022) to determine the amount of water in the sand before being subjected to further analyses. Following this, the sand samples were oven-dried to prepare them for further analysis as described by Afolayan et al. (2023).



Source:fieldwork, (2014)

Figure 1. Sampling points in the Osun River

### Laboratory Analysis

Falling head permeability tests (FHPTs) were conducted according to the procedures outlined by Das (2020). The test results were derived using the standard mathematical model indicated in Equation (1):

$$K=\frac{2.303aL}{At}\log\frac{h_1}{h_2} \qquad (1)$$

In this context, 'a' is the burette's cross-sectional area, 'A' is the cross-sectional area of the permeameter, 'L' denotes the length of the sample within the permeameter, '$h_1$' is the initial head, '$h_2$' is the final head, 't' is the time interval during which the head decreases from '$h_1$' to '$h_2$', and 'K' stands for the hydraulic conductivity coefficient in cm/s. The results of the hydraulic property tests on the river sand were analyzed using the regression model available in the Statistical Package for the Social Sciences (SPSS), as detailed by Reynald (2021). The friction factor was obtained from the regression models given by:

$$f=-1.314\ln Re \qquad (2)$$

Where *Re* is the Reynolds number obtained from:

$$Re=59.75Q-1.627e^{5}Q^{2}-4.642e^{-5} \qquad (3)$$

Where Q represents the flow rate. Furthermore, the hydraulic gradient (i) was obtained from the regression model:

$$i=55.919e^{3}v-120.821e^{6}v^{2}-4.666 \qquad (4)$$

where v is the velocity of flow.

## Results and Discussion

### Hydraulic Properties of Sand Samples

Table 1 summarizes hydraulic properties across sample locations. The effective grain size of sand samples ranged from 0.20 mm to 0.32 mm, with most samples between 0.30 mm and 0.31 mm. Sample location ‘F’ exhibited the smallest D10 at 0.20 mm, indicating more granular sand compared to other locations, which often results in higher resistance to flow (Nelson & Williams, 2019). Flow velocities varied from 1.57 cm/s to 2.41 cm/s across the different locations. Sample locations 'B' and 'E' showed the highest velocities at 2.41 cm/s, while Sample location 'A' showed the lowest at 1.57 cm/s. Higher velocities are generally observed in coarser sands with larger pore spaces.

Table 1. The hydraulic properties of sand samples

| Properties | Sample Locations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| Area | 78.55 | 78.55 | 78.55 | 78.55 | 78.55 | 78.55 | 78.55 | 78.55 |
| Diameter ($D_{10}$) | 0.32 | 0.30 | 0.30 | 0.30 | 0.30 | 0.20 | 0.31 | 0.31 |
| VF($\text{x}10^{-2}$) | 1.57 | 2.41 | 2.18 | 2.11 | 2.41 | 1.60 | 1.92 | 2.01 |
| FR(Q)$\text{x}10^{2}$ | 1.23 | 1.89 | 1.71 | 1.66 | 1.89 | 1.26 | 1.51 | 1.58 |
| RN($\text{x}10^{-6}$) | 1.39 | 8.53 | 7.75 | 7.51 | 8.58 | 3.79 | 7.04 | 7.39 |
| $F_F$($\text{x}10^{6}$) | 45.85 | 7.5 | 8.26 | 8.52 | 7.46 | 16.90 | 9.09 | 8.67 |
| HG(*i*) | 1.09 | 1.83 | 1.74 | 1.72 | 1.78 | 1.21 | 1.68 | 1.69 |
| HC(K)$\text{x}10^{-2}$ | 1.43 | 1.32 | 1.25 | 1.23 | 1.35 | 1.32 | 1.14 | 1.19 |
| Remarks | HMS | HMS | HMS | HMS | HMS | HMS | HMS | HMS |

HMS= High medium sand; A= Area (cm$^2$); VF= Velocity of flow (cm/s); FR= Flow rate (cm$^3$/s); RN= Reynolds Number; $F_F$= Friction Factor; HG= Hydraulic Gradient; D10 represents the grain size at which 10% of the particles are smaller, measured in millimeters, and HC(K)= Hydraulic Conductivity (cm/s)

Flow rates ranged from $1.23 \times 10^2$ cm$^3$/s to $1.89 \times 10^2$ cm$^3$/s. Similar to velocity measurements, samples on locations 'B and E' had the highest flow rates suggesting these samples allow more fluid passage per unit time, likely due to their coarser texture (Wang et al., 2019). On the other hand, Reynolds numbers ranged between $1.39 \times 10^6$ and $8.58 \times 10^6$. Higher Reynolds numbers in samples locations 'B and E' indicate turbulent flow while lower values in samples like 'A and F' suggest laminar flow conditions. This transition from laminar to turbulent flow can affect the stability and performance of structures built on or within these sands (Yan et al., 2022).

The friction factor varied from $7.46 \times 10^6$ to $45.85 \times 10^6$. Sample location A had the highest friction factor, indicating greater resistance to flow. This is consistent with its higher effective grain size and lower velocity of flow (Hohenbrink et al., 2023). The hydraulic gradient ranged from 1.09 to 1.83. The gradient measures the slope of the hydraulic head and indicates the driving force for the flow through the sand. Figure 2 in the study illustrates the relationship between the velocity of flow and hydraulic gradient across different sample locations along the Osun River. The graph is essential for understanding how these two parameters interact within the hydraulic properties of sand samples. Higher gradients in sample locations B and E suggest a steeper slope and thus a higher driving force for fluid movement (Liu et al., 2022). In contrast, the velocity of flow varies significantly across the sample locations, with locations B and E achieving the highest velocities at 2.41 cm/s. This is indicative of coarser sand textures at these sites, which facilitate faster fluid passage compared to finer sands found at other locations. The hydraulic conductivity values varied from $1.14 \times 10^{-2}$ cm/s to $1.43 \times 10^{-2}$ cm/s, with the highest value observed in Sample location A and the lowest in Sample 'H'.

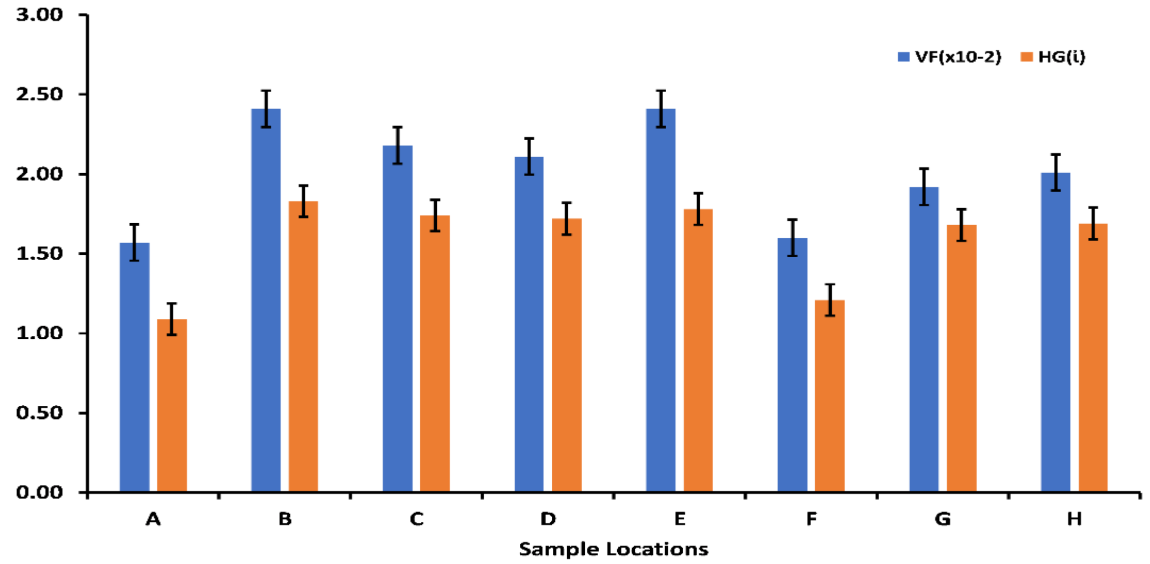


Figure 2. The relationship between the velocity of flow and hydraulic gradient across different sample locations along the Osun River.

Higher hydraulic conductivity in Sample A (Figure 2) aligns with its larger grain size and higher flow rate, reflecting better permeability (Ma et al., 2018; Yang et al., 2020). Recent studies have explored similar hydraulic properties in river sands, reinforcing the observations from this study. For instance, research by Gupta et al. (2022), Qiao et al. (2022), and Zhang et al. (2023), demonstrated that coarser sands exhibit higher hydraulic conductivities and flow rates. This is consistent with the present study findings. Similarly, Johnson et al. (2022) found variations in effective grain size significantly impact hydraulic gradient and flow behavior, supporting the observed differences among samples. Findings reveals clear correlation between grain size, hydraulic conductivity, and flow dynamics. The results are consistent with established theories and recent empirical studies, highlighting the importance of grain size and other factors in determining the hydraulic behavior of sand.

### Analytical Model in Porous Media

The hydraulic property tests conducted in this study enabled the development of a model in the correlation of friction factor with the Reynolds number, Reynolds number with flow rate, and hydraulic gradient with flow velocity are summarized in Tables 2 to 4. The negative correlation between the friction factor and Reynolds number (Table 2), as indicated by the coefficient of ln(Re) (-1.314), suggests that as flow transitions from laminar to turbulent, the friction factor decreases. The high T-value (-44.831) and significance level ($p = 0.000$) confirm the strong statistical relationship, implying that the frictional resistance of the sand samples reduces as the flow rate increases.

Table 2. The relationship modeled between the friction factor & the Reynolds number

| Coefficients | | | | | |
|---|---|---|---|---|---|
| | UC | | SC | T | Sig. |
| | B | Std. Error | Beta | | |
| ln(Re) | -1.314 | .029 | -.999 | -44.831 | .000 |

UC: Unstandardized Coefficients; SC: standardized Coefficients

The model shows a significant positive correlation between Reynolds number and flow rate (Q) in Table 3 with a coefficient of 59.755, indicating that increasing flow rate enhances the turbulence within the porous media. However, the negative quadratic term ($-1.63\times10^{7}$) suggests that at higher flow rates, the increase in Reynolds number diminishes, possibly due to increasing flow resistance. The high significance values ($p < 0.05$) validate the reliability of this model.

Table 3. The model relationship between Reynolds number (Re) and flow rate (Q)

| Coefficients | | | | | |
|---|---|---|---|---|---|
| | UC | | SC | T | Sig. |
| | B | Std. Error | Beta | | |
| Q | 59.755 | 15.696 | 5.891 | 3.807 | .013 |
| Q ** 2 | -16265934.009 | 5048762.713 | -4.986 | -3.222 | .023 |
| (Constant) | -4.642E-005 | .000 | | -3.876 | .012 |

UC: Unstandardized Coefficients; SC: standardized Coefficients

The strong positive coefficient (55,919.058) for flow velocity (v) in Table 4 suggests that an increase in velocity significantly raises the hydraulic gradient, indicating greater energy loss in the porous medium. The negative quadratic term ($-1.21\times10^8$) implies a decreasing rate of increase in the hydraulic gradient at higher velocities, possibly due to turbulence effects. The highly significant p-values ($p < 0.01$) affirm the robustness of this relationship.

Table 4. The model relationship between hydraulic gradient (*i*) and velocity of flow (v)

| Coefficients | | | | | |
|---|---|---|---|---|---|
| | UC | | SC | T | Sig. |
| | B | Std. Error | Beta | | |
| *v* (cm/s) | 55919.058 | 8218.440 | 6.508 | 6.804 | .001 |
| *v* ** 2 (cm/s) | -120821359.524 | 20630835.377 | -5.601 | -5.856 | .002 |
| (Constant) | -4.666 | .804 | | -5.807 | .002 |

UC: Unstandardized Coefficients; SC: standardized Coefficients

These findings from this study are in agreement with those of Afzali et al. (2019), who observed faster fluid flow in homogeneous compared to heterogeneous porous media under the same hydraulic gradient. Furthermore, the study found that the velocity of fluid is higher in mixed heterogeneous media than in layered heterogeneous media. Therefore, for effective seepage control, selecting a material with lower permeability, such as a layered heterogeneous medium composed of sand samples with varying porosities arranged in descending order (DHLT), is recommended for optimal performance.

## CONCLUSION

This study reveals significant variations in the hydraulic properties of sand samples from different locations along the Osun River. Key parameters such as effective grain size, flow velocity, flow rate, Reynolds number, friction factor, hydraulic gradient, and hydraulic conductivity exhibited distinct patterns. Coarser sands from locations B and E demonstrated higher hydraulic conductivities and flow rates, indicating better permeability, while granular sands from location F showed greater resistance to flow. The findings emphasize the need for site-specific analyses in construction and water management projects to accurately predict fluid flow and permeability. The results align with international standards, classifying the sand as high-medium permeability with laminar flow, as indicated by Reynolds numbers below one. By incorporating essential hydraulic parameters, this study provides valuable insights into sand bed performance, environmental hazard assessment, and seepage control in dam management, reinforcing its practical significance for water resource management.

## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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