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Dynamic Hydraulic Conductivity and Seasonal Clogging of Filters in Small Earth Dams: Al-Wand Earth Dam as a Case Study

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ABSTRACT

The seasonal variation in the level of the river influences the quantity of water that these dams can contain. In this study, the effect of changing the water level of the river on the stability and performance of a filtration system at a small earth dam is evaluated for a period of 10 years. The article discusses the influence of alternate droughts and heavy rain periods on dam water storage and highlights that hydraulic conductivity is not constant, as is usually considered in leakage studies. Specifically, the study focuses on the Al-Wand Earth Dam. The study analyzed the daily water pressure data from 2015 to 2025 using GeoStudio (SEEP/W). The research was carried out in four steps: data gathering, computer modelling, seasonal decomposition, and validation calculations. This process showed considerable differences between the theoretical assumption of continuous permeability and the actual situation in the field. Thus, a hydraulic analysis was carried out and divided into two seasonal models: winter/filling and summer/low water level. The results showed remarkable long-term accuracy with cumulative Nash-Sutcliffe efficiency values of 98 % for the winter model and 95 % for the summer model. Importantly, the study observed that the effective permeability at summer low water levels reduced by nearly 88% relative to the design values, a substantial departure from the safety limits.

Keywords: Water level fluctuations, Seepage analysis, Earthen dam, Model, Geo studio software.

1. INTRODUCTION

An earth dam is created from very dense soil. It is called a sort of reservoir constructed on a hill or wedge that blocks a canal. Other materials used in earth dams besides soil include rock and clay **(Ade, 2019)**. Dams are constructed to retain water for consumption and horticultural use, to control the flow of rivers, limit the risks of flood and drought, produce electricity, etc. Earthen dams cover a wide range of variants, being completely homogeneous

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element embankment dams and inhomogeneous embankment dams (zonal as well as reticular) **(Abdel-Kawy et al., 2021)**. Dams are primarily made of earth and Rock-fill materials. Therefore, they are commonly known as embankment dams or fill-type dams. Earth-fill dams are simple structures that can resist sliding and overturning due to their self-weight **(Athani et al., 2015).** Seepage is a very essential problem which has to be studied and regulated carefully during the design of earth dams. Too much seepage can undermine the stability of the dam and lead to its failure. **(Al-Hadidi, 2024).** Consequently, water seepage from the body and foundation of earthen dams can cause significant water loss, especially in arid regions, and can critically compromise the overall stability of the structure **(Abass and Najeeb, 2018)**. Seepage flow through intricate foundations is among the main causes of dam failure. To anticipate this problem, seepage modelling and analysis are frequently carried out. This study evaluated the seepage behavior in an earth dam with complicated foliated rock foundations **(Malik, and Karim, 2020).** Failure of earthen dams happens frequently due to water seepage through the porous infill materials **(Athani et al., 2015).** The program SEEP/W was used to calculate the amount of seepage through the homogeneous and non-homogeneous earth dam with known dimensions, where the relation between the seepage and water height in the upstream of the dam to its length for saturated soil was nonlinear when the dam is homogeneous. For the non-homogeneous dam, the relation was linear, and the amount of seepage rises with the height of water in the upstream to its length **(Noori and Ismaeel, 2011).** Uncontrolled seepage or improper material and filter zonation in earthen dams are the main causes of piping failures **(Talukdar et al., 2019).** Anomalous seepage through the foundations and cores of earthen dams can occur. As a catalyst for internal erosion, anomalous seepage—including high and/or concentrated seepage—is the main reason why earthen dams collapse **(Ikard et al., 2015)**. Statistics indicate that 40% of dam failures are caused by foundation seepage, underscoring it as a major factor in structural integrity **(Suad and Al-Hadidi, 2025)**. Seepage becomes highly undesirable and dangerous if it compromises the dam by causing internal erosion or piping, where fine materials erode and move out of the structure, or when it leads to dam overflow **(Jamel, 2018)**. Because of internal granule movement and seepage transfer, unregulated water flow remains one of the most common causes of earth dam collapse **(Alzamily and Abed, 2022a)**. The main factor causing erosion, scouring, and pipe failure in earth embankments is seepage flow. Grain movement in soil can result from water flowing through the soil **(Salem et al., 2019).**

The failure of earth dams generally results from a combination of structural instability, hydraulic conditions, seepage through the dam body, and rapid drawdown scenarios; therefore, determining the safety factor for dam slope stability across all possible operational conditions is essential to ensure overall safety **(Kirra et al., 2015)**. The infiltration of water into the ground under an earth dam is a significant factor in creating instability. The world was the supposed piping event, which is what happens even with the unlimited movement of soil particles out to free exits, or into coarse openings; it can happen via the or its foundation soil or earth embankment **(Omofunmi et al., 2017)**. The water leak speed under dams is seen as a crucial factor when they are designed. It depends on what the ground and dam are made of **(Farooq et al., 2015)**. Stability and seepage analysis for earthen dams are very important to maintain the stability of the structure. Embankments of earthen dams must be designed to ensure stability against any type of force conditions that develop in the life of the structure **(Devi et al., 2017)**. For dirt dams, the middle core is used to stop water leaks. The water inside the dirt is kept low by this core **(Alzamily and Abed,**

2022b). The shape and material of the core are very critical. If the core is made wider or more sloped, the dam is made less safe. This is because the core is weaker than the outside layers. Its power is lost very fast when water is emptied quickly **(Aziz et al., 2023).**
Emptying water very fast is seen as the most dangerous thing for the front of the dam. When water pressure goes down suddenly, the wet dirt is pushed to slide back. Heavy forces are made by this, and the dam can be broken **(Fattah et al., 2017)**. To stop the dam from failing in case of water level fluctuation, a common engineering practice is to install horizontal drains on the water-facing side. The number of drains you need just depends on how fast the water drops and how easily water flows through the soil **(Al-Khyat et al., 2025)**. To analyze these complex seepage and stability issues accurately, modern engineering relies heavily on numerical modeling, specifically using general-purpose partial differential equation solvers and soil property functions to evaluate saturated and unsaturated seepage problems in two-dimensional steady-state and transient conditions, as well as three-dimensional soil systems **(Thieu et al., 2001)**. Among these tools, Geo-Studio, a CAD-style software developed by Geo-Slope International, is widely utilized to solve groundwater and seepage problems in permeable soils utilizing the Finite Element Method (FEM) **(Mohammed and Ameen, 2024)**. SEEP/W allows for the comprehensive analysis of groundwater seepage and the dissipation of overload pore-water pressure inside permeable materials like soil and stone, accommodating scenarios that range from simple, saturated steady-state problems to complicated, time-dependent saturated and unsaturated conditions across civil, geotechnical, hydrogeological, and mining engineering projects **(Irzooki, 2016)**.
Numerous researchers have applied these finite element procedures to evaluate dam stability and seepage control under various operational circumstances. For example, studies utilizing the Geo-Studio software have demonstrated that as the permeability of structural layers increases, seepage through the dam body and exit slope decreases, with safety factors for upstream and downstream slope stability consistently meeting minimum requirements across maximum, average, and minimum reservoir levels **(Zedan et al., 2022)**. Investigations into the Al-Wand dam utilized SEEP/W to determine that reducing the thickness of the core slightly minimizes the quantity of leakage, while also analyzing the variations in seepage when the dam is constructed without an upstream filter **(Jassama and Sinan, 2020)**. The GEO-Studio subprograms (Seep/w, Slope/w, and Quake/w) utilized in this study are finite element programs employed to investigate the variations in seepage field, stress field, displacement field, and stability coefficient of the slope under diverse rainfall conditions, focusing on seepage mechanics, and to elucidate the alterations in unsaturated soil and the impact of earthquakes on earth dams **(Tan et al., 2023)**. The effect of seepage in an earth fill dam has been examined using the finite element approach with the SEEP2D program. This is to find out the quantity of seepage through the dam. The seepage was examined for the effect of varied water heads of the reservoir. The results indicated that the seepage quantity increased with any rise in the water heads. It is observed that the clay core has an important impact on reducing the seepage quantity and the existing gradient **(Al-Mansori et al., 2020)**.
Beyond earth dams, the application of Geo-Studio models has been instrumental in evaluating seepage control in other hydraulic structures, such as the Al-Kifil regulator. Combining analytical and empirical approaches, numerical models proved that introducing structural breakers, like concrete piles, successfully controls seepage and lowers the safety factor against lifting pressure more effectively than traditional pull-out techniques, thereby preventing long-term water seepage **(Thieu et al., 2001).** This investigation shown that

water level fluctuations in reservoirs lead to a very dynamic response of the filter permeability, specifically caused by a seasonal flow reversal that leads to mechanical blockage. This event leads to a large drop in the effective permeability, up to about 88% during the low-water periods and radically changes the internal hydraulic stability of the dam.

Traditional leakage assessments have traditionally treated filter permeability as a constant variable, but this study indicates that hydraulic conductivity is intrinsically dynamic. This study fills an important gap in the scientific literature by quantifying the influence of seasonal flow reversals on mechanical obstruction. The results show a considerable loss in effective permeability of ~88%. This variability should be included for a better assessment of the internal hydraulic stability of earth dams, which is commonly neglected in the classical constant permeability models. The purpose of the study is to simulate and evaluate the variation of the water level in the Al-Wand River during the year and to analyze the effect of it on the stability of a small earth dam.

2. METHODOLOGY

This study tests the seepage in Al-Wand Earth Dam and how well its filters work. To do this, the reverse is looked at by using real numbers. Actual measurements of water pressure (2015-2025) were taken daily and entered into GeoStudio (SEEP/W). This helped to see how the dam actually operates in real life and not simply rely on the initial paper plans. The task was done in four easy steps: gathering the data, developing the computer model, dividing the year into seasons, and finally conducting some math to make sure our conclusions were correct.

2.1 Study Area and Data Acquisition

Al-Wand dam is a clayey-core earth dam located 3 km south-east of Khanakeen, Dayala and 6km from the border between Iraq and Iran. Al Wand dam on Al Wand River stores water from western Iran. The catchment area is 3204 km^2, and the dam length is 2.8 km. The surface area of the dam is 6,207,704 m^2, and the storage volume at the level of 215 m is 37,924,168 m^3 according to the design requirements for the dam. The location of Alwand Earth Dam is shown in **Fig.1**.

A complete daily dataset (Resident Engineer Department of AL Wand Dam) was compiled for the operational period from January 2015 until 2025. The data set consists of reservoir water levels and the accompanying pore water pressure readings (HO: Observed piezometric head) from three piezometers put in the embankment and the foundation, giving a good basis for calibration

2.2 Numerical Modeling Configuration

The seepage analyses were performed using the GeoStudio (SEEP/W) program, and the governing differential equations of the transient flow in saturated/unsaturated soil were solved using the Finite Element Method (FEM). The geometry of the model was defined based on the official cross-sections of the dam (As-Built). The hydraulic boundary conditions were set as follows:

- Upstream Boundary: Specified time-dependent reservoir head function H(t).
- Downstream Boundary: The potential seepage face of the dam toe was assigned a zero pressure head (P=0).

Initial material characteristics and hydraulic conductivity functions were assigned based on original geotechnical design reports and iteratively calibrated.

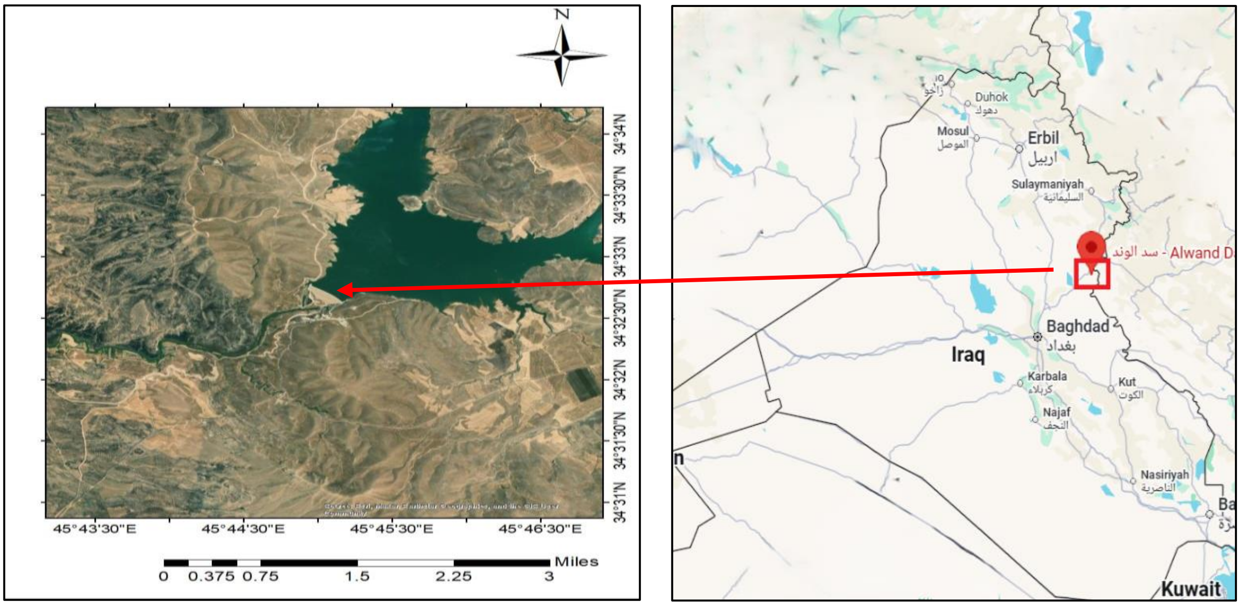

Figure 1. Location of Al-Wand dam (Google Earth)

2.3 Seasonal Segmentation Strategy

In this study, instead of assuming a constant hydraulic conductivity (k), the year was divided into two seasons, and a separate model was employed for each season as follows:

1 .Winter/Filling Phase (Model 1): November 1 – July 1. This time period is steady state seepage, flow from core to filter. This state is favorable to physical clogging, when small particles are captured in the spaces of the filter, reducing permeability.

2 .Model 2 (Summer/Drawdown Phase): Covering the period from July 15th to October 15th. This period is the key fast-drawdown condition. During this phase, the reversal of hydraulic gradients promotes suffusion (internal erosion), which flushes tiny particles out of the filter ("unclogging"), effectively enhancing its permeability.

2.4 Statistical Evaluation and Validation

The mathematical models were checked very well. Simulated Heads (H_S) were compared with Observed Field Heads (H_O). To know the mistakes, a math tool called RMSE was used. To know how strong the model is, another tool called EF was used. Also, a special test was done on the 2022 water drop data. The exact percentage difference between the design permeability (k_{origin}) and the actual operational permeability now (k_{now}) was calculated using Eq. (1).

$$\text{Decreasing Ratio}(\%) = \left[\frac{(K_{new} - K_{origin})}{(K_{origin})}\right] \times 100 \quad (1)$$

2.5 Geotechnical Characteristics of Al-Wand Dam Materials

The following geotechnical properties of modern dam construction materials need to be specified in the software for modelling and calculating the amount of seepage, as shown in **Table 1.**

Table 1. Geotechnical characteristics of Al-Wand dam.

Location	γ_{total} (kN/m^3)	Permeability (m/sec)
Shell	18	0.001
Filter	18	9.9×10^{-8} - 8.5×10^{-7}
Core clay	18	4.8×10^{-9}
Foundation	18	8×10^{-5}

3. SEEPAGE ANALYSIS OF AL-WAND DAM

3.1 Modeling Program

The SEEP/W software developed by Geo-Slope International is a CAD-style software tool that analyses seepage and groundwater problems in porous soil media using the finite element method (FEM). This software is designed to disperse the excess pore pressure within porous materials such as soil and rock and has been limited to the analysis of groundwater seepage and leakage problems. The governing equation of the SEEP/W system is the partial differential equation (PDE). The Alwand earthen dam model was analyzed using the program as shown in **Fig. 2**. The cross-section of the dam shows the geometric arrangement of its zones, as **Fig. 3.**

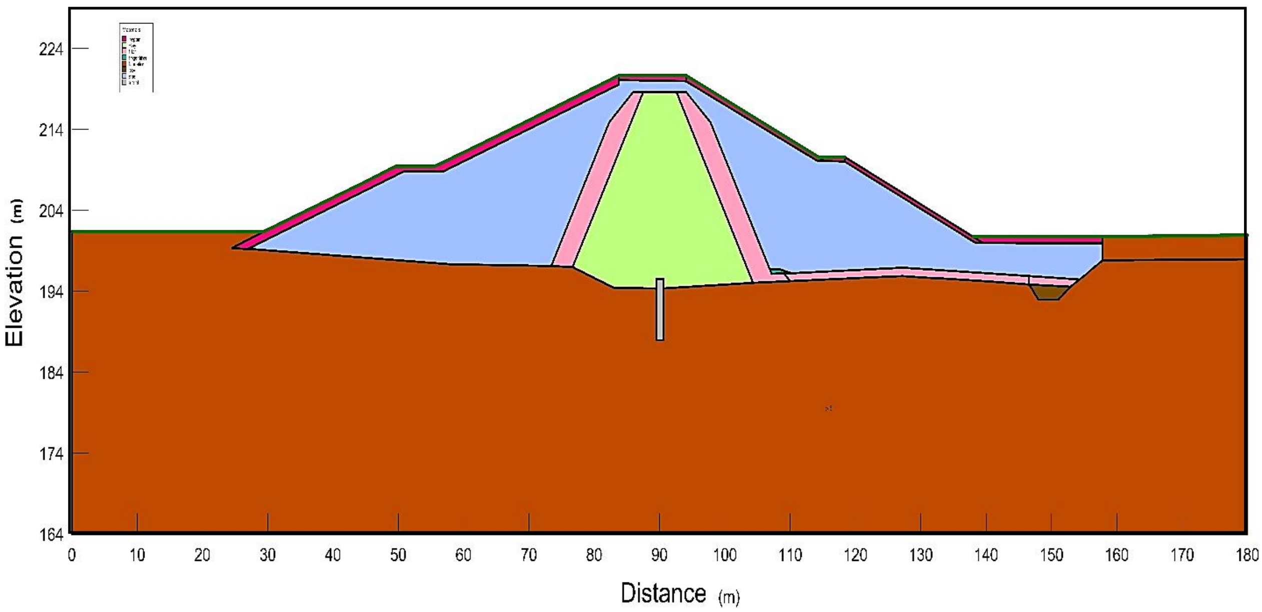

Figure 2. 2D Al-Wand earth dam model

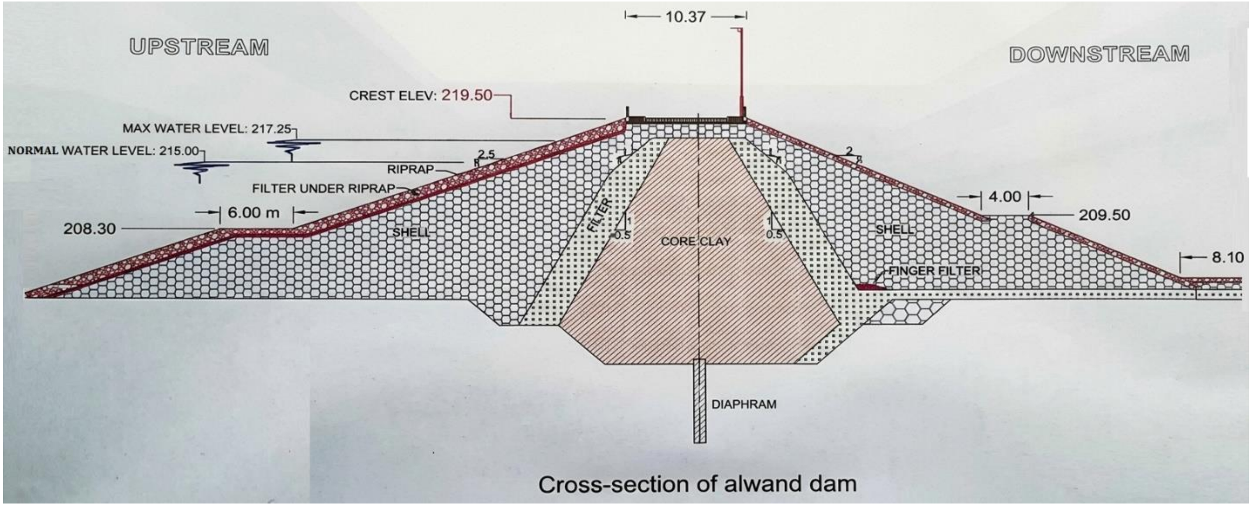

Figure 3. Cross-section of Al-Wand earth dam model, **(Iraqi Ministry of Water Resources, 2025)**.

3.2 Formed Mesh by Using Seep/W Software

One station at the Alwand Dam, Station 629, was selected, measuring 180 meters in length and 56.675 meters in height. A suitable finite element grid consisting of 31,376 nodes and 30,967 four-way nodes, spaced 0.5 meters apart, was chosen. The finite element grid comprises four types of elements: triangular, square, rectangular, and trapezoidal. These elements were selected after trials to achieve the required accuracy, as illustrated in **Fig. 4**.

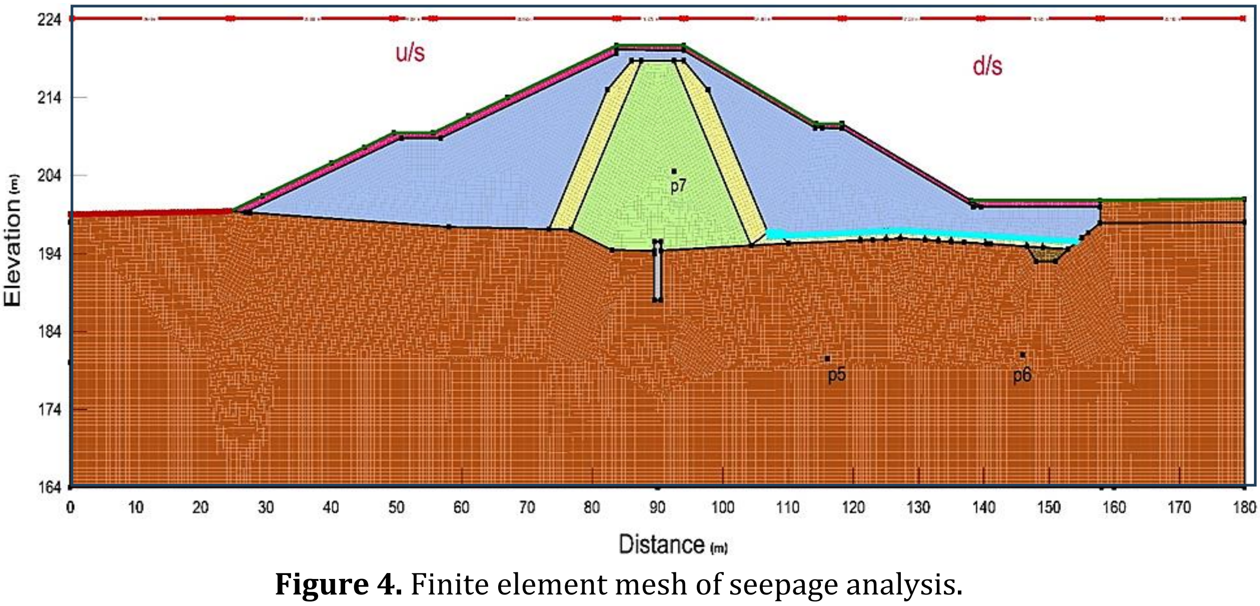

Figure 4. Finite element mesh of seepage analysis.

4. RESULTS AND DISCUSSION

This section presents the findings of the back-analysis for the decade 2015–2025. Two models were created for each time period estimated, its own model. The cross sections of the model of the dam below were obtained by applying the SEEP/W2024 program. where the first model represents the time period from (01/11 to 01/07). The cross-section of the first model is shown in **Fig. 5.** The second model represents the time period from (15/07 to 15/10) sand is shown in **Fig. 6**.

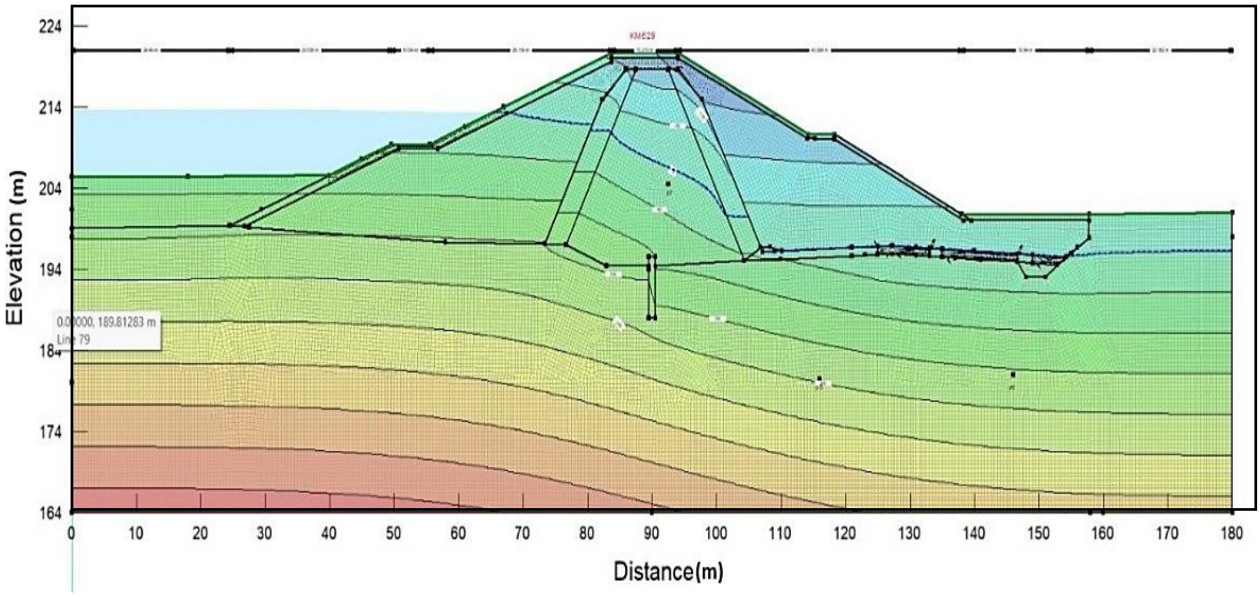

Figure 5. Model no. (1) of Alwand earth dam at level 214.65 m.

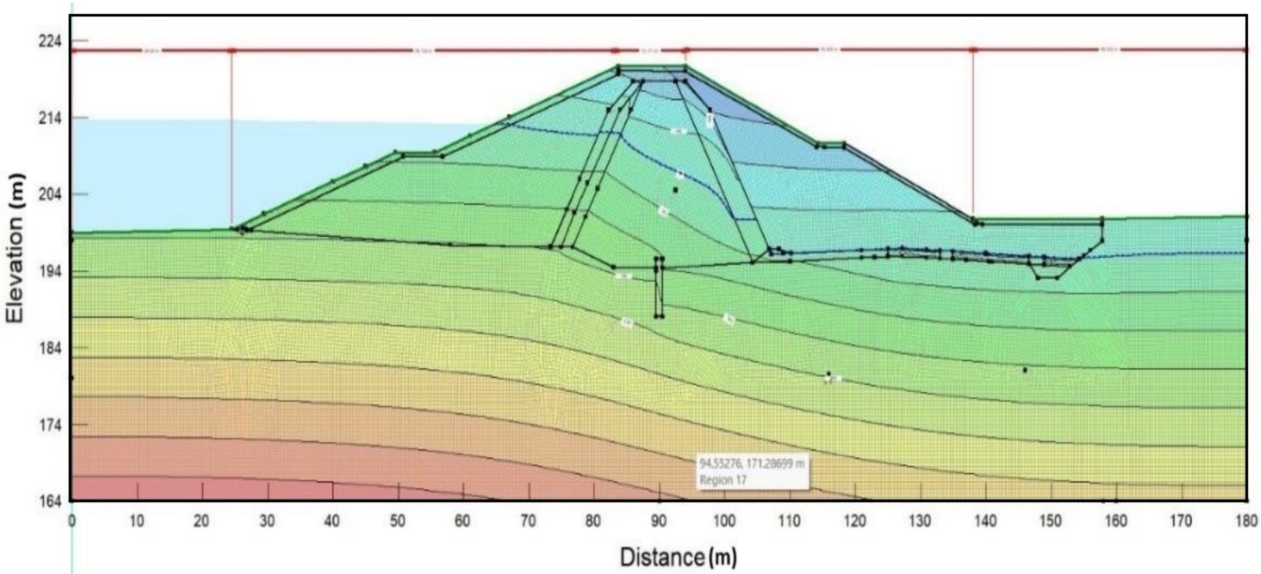

Figure 6. Model no. (2) of Alwand earth dam at level 214.67 m.

4.1 Justification for Variable Permeability (The Necessity of Two Models)

Before presenting the statistical performance, it is crucial to state the reason for separating the analysis into two models. Preliminary analysis of the 10-year dataset revealed that a single permeability value (k) could not accurately represent the dam's behavior year-round. The analysis confirmed that the filter permeability is not static but changes seasonally due to:

- Significant changes in water viscosity between winter and summer.
- The reversal of flow direction during rapid drawdown causes an "unclogging" or "backwashing" of fine particles within the filter, effectively increasing its hydraulic conductivity.

This finding necessitated the assignment of higher permeability values for the Summer/Drawdown season to achieve a valid calibration. The statistical performance of these two optimized models is presented below.

4.2 Piezometer Reading and Pore Water Pressure of Models

The results obtained from the models were compared with the piezometer reading for the two models as follows:

4.2.1 Model 1 (Winter/Filling)

Period: (1 Nov – 1 July) for years 2015–2025. This model represents the steady-state or slow-filling condition. The flow direction is consistently from the core towards the filter, leading to particle stabilization (partial clogging). **Figs. 7 to 9** show the results obtained from the model, where the piezometer reading (Observed Head) (H_O) and pore water pressure head (Simulated Head) (H_S).

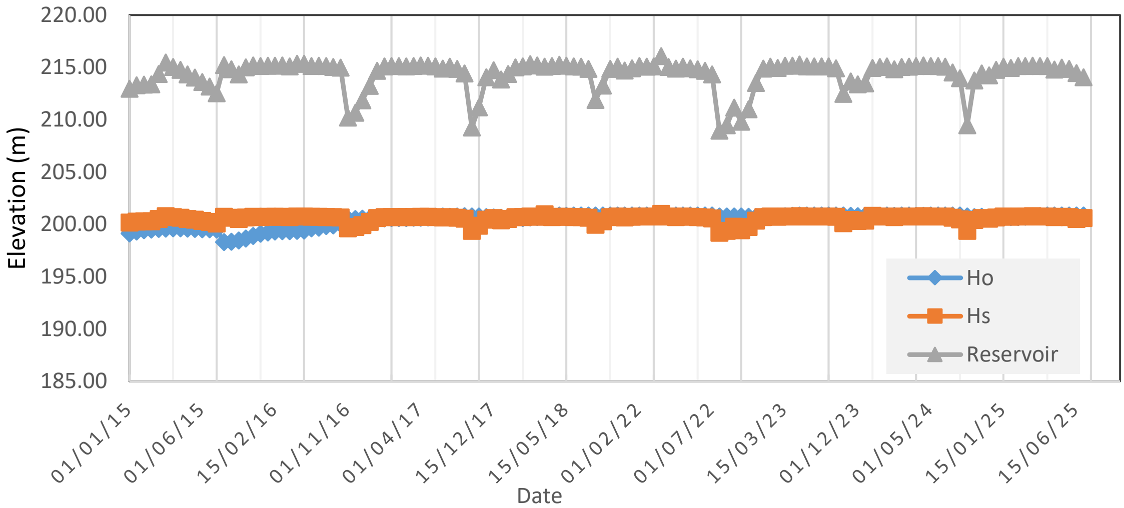

Figure 7. Piezometer no. (5) of Model 1 (H_O), (H_S), and reservoir level.

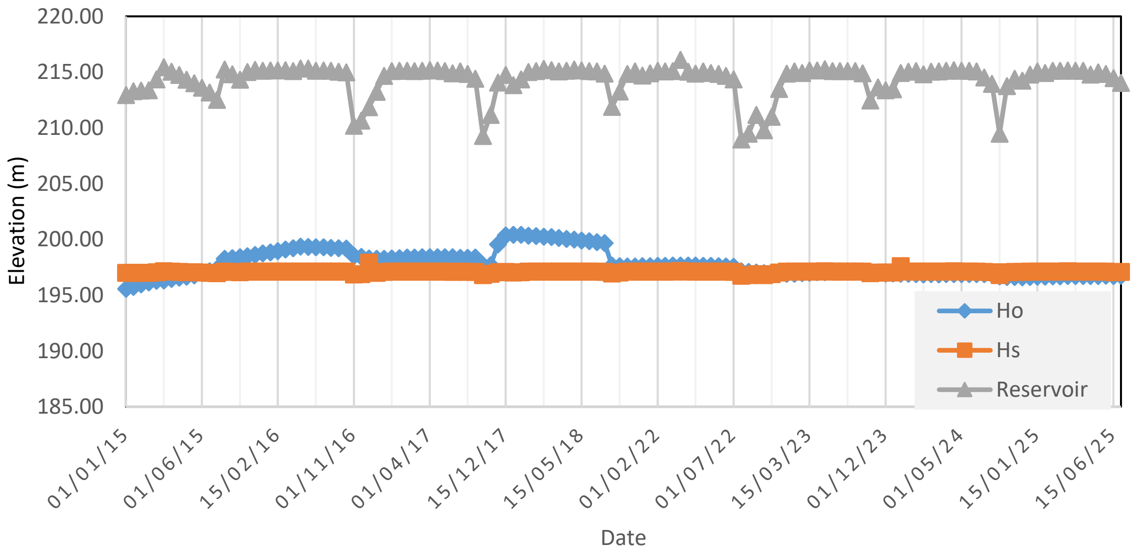

Figure 8. Piezometer no. (6) of Model 1 (H_O), (H_S), and reservoir level.

4.2.2 Model 2 (Summer/Drawdown)

Period: (15 July – 15 Oct) for the years 2015–2025. This model represents the critical loading condition. Despite the complex hydraulic gradients caused by rapid drawdown, the model achieved high accuracy after adjusting for increased permeability. **Figs. 10 to 12** show the results obtained from the model, where the piezometer reading (Observed Head) (Ho) and pore water pressure head (Simulated Head) (Hs).

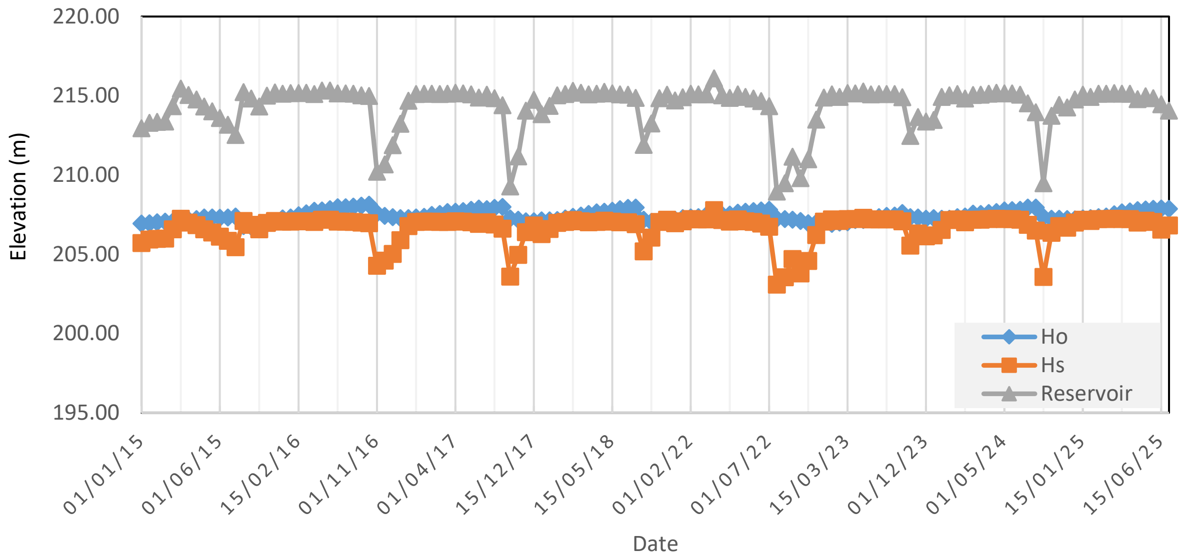

Figure 9. Piezometer no. (7) of Model 1 (Ho), (Hs), and reservoir level.

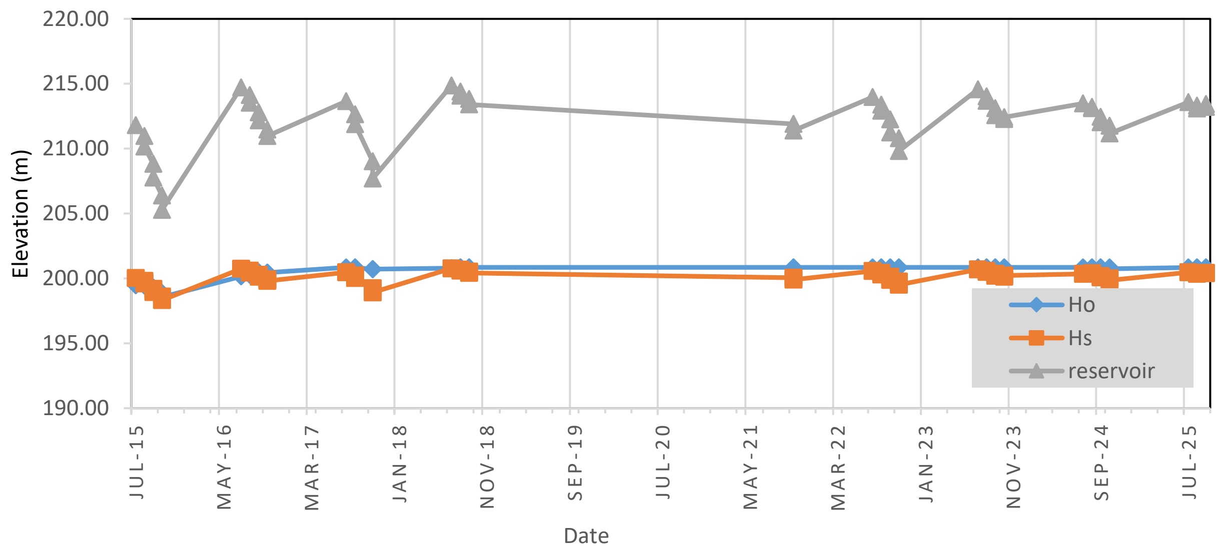

Figure 10. Piezometer no. (5) of Model 2 (Ho), (Hs), and reservoir level

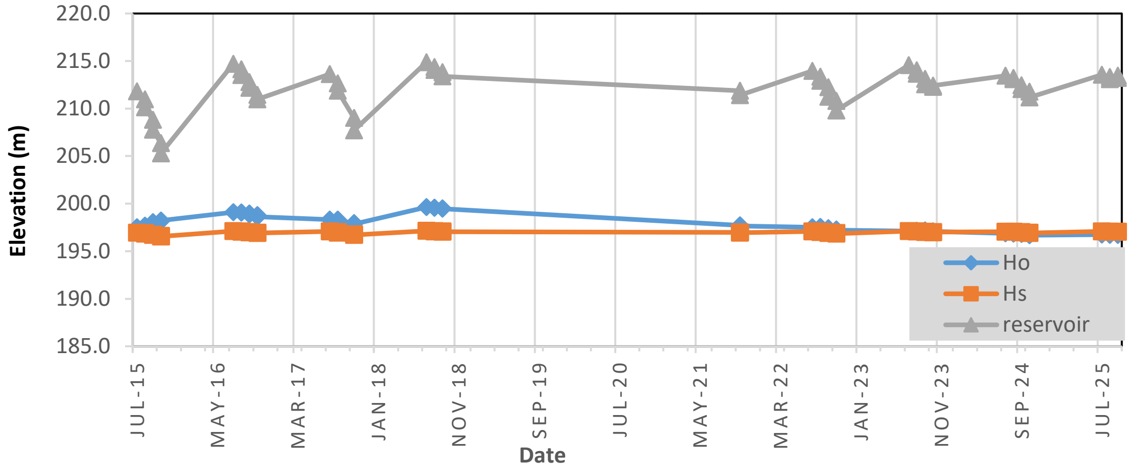

Figure 11. Piezometer no. (6) of Model 2 (Ho), (Hs), and reservoir level

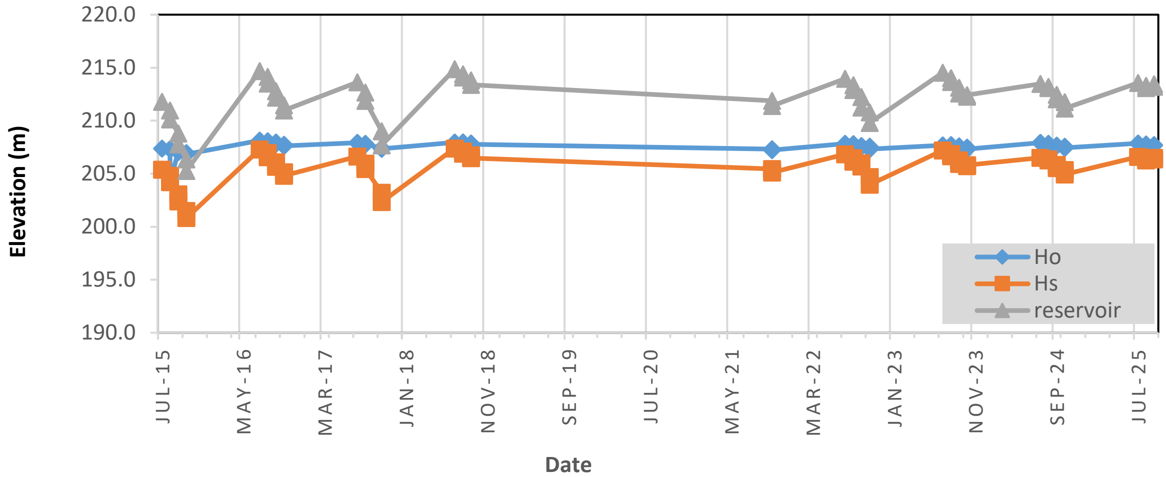

Figure 12. Piezometer no. (7) of Model 2 (Ho), (Hs), and reservoir level

The models' performance and validity are evaluated using available data shown in **Figs. 7-12**, by Root Mean Square Error (RMSE) and Model Efficiency (EF). The statistical parameters are shown in **Table 2** and **Fig. 13** for two models.

Table 2. Seasonal Seepage Analysis (Two Seasons) summary.

Model NO.	**K (m/sec)**	**Mean Error (ME)**	**Root Mean Square Error (RMSE)**	**Model Efficiency (EF) %**
Model 1(winter)	$8.5* 10^{-7}$	0.3545	0.589	98.17
Model 2 (summer)	$9.9 *10^{-8}$	0.729	0.956	95.37

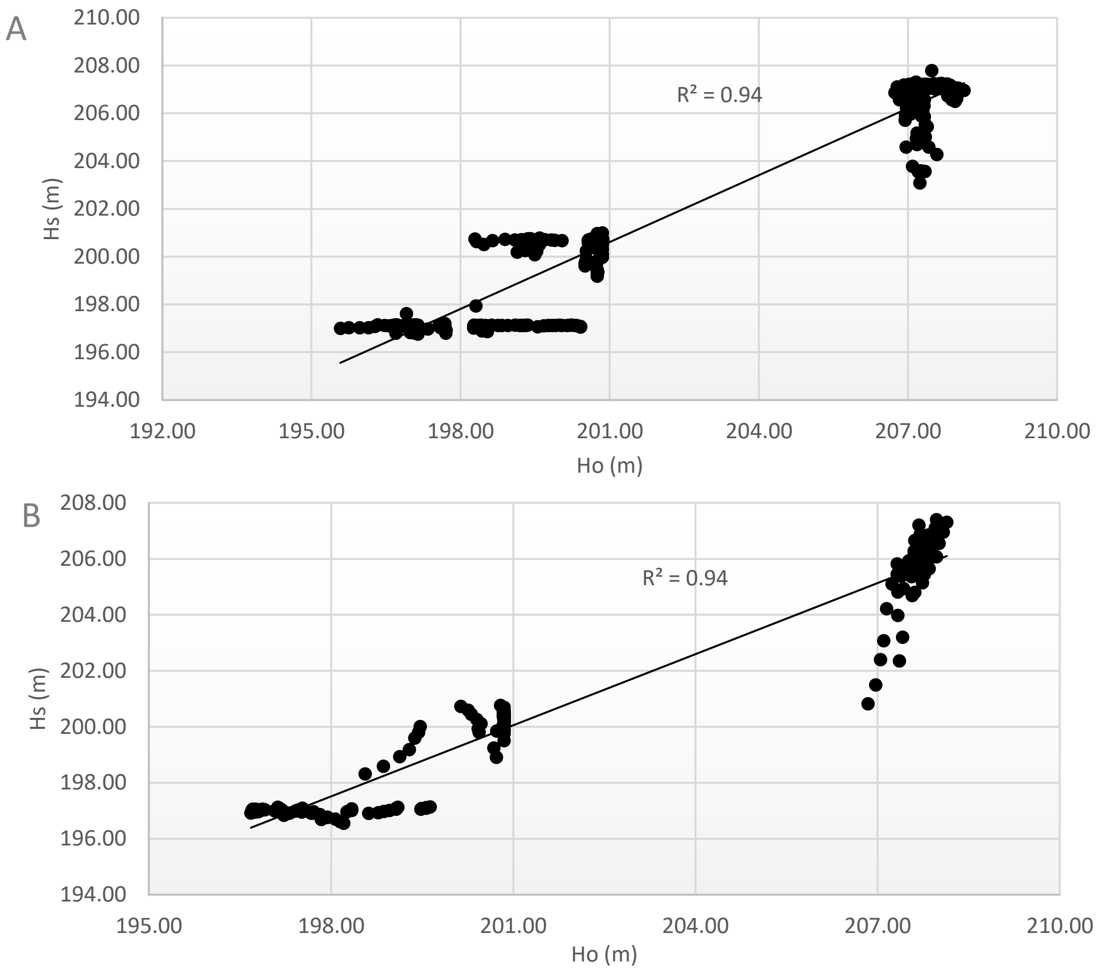

Figure 13. Root Mean Square Error (RMSE) for (A) model 1 and (B) model 2

4.3 Quantification of Permeability Change

To find out how much the filter changed from the first design, the SEEP/W program was used to look back at the numbers. The focus was on the year 2022 when the water went down very fast, because it was the hardest time for the dam. Three steps were followed to calculate this:

- First, the program was run using the old hydraulic conductivity from the first design (K_{origin}). The pressure numbers from the program were very different from the real numbers in the field. This showed that the real water pressure went away faster than what the old design expected.
- To make the mistake between the program and the real data very small, the filter hydraulic conductivity was changed step by step in the program. This was done until a "best match" was found. This match gave the new working speed (K_{now}).
- The amount of the hydraulic conductivity drop was calculated by using this percentage formula. The decrease in hydraulic conductivity was calculated using Eq. (1).

It is seen that the summer hydraulic conductivity (k_{summer}) is 88.35% less than the old design speed (k_{origin}), as shown in **Fig. 14**. The physical block is shown by this big 88.35% number. In the summertime, water is pushed back to the lake. Fine particles are moved by this water and stuck in the filter spaces. A very heavy block and a big fall in water speed are achieved by this.

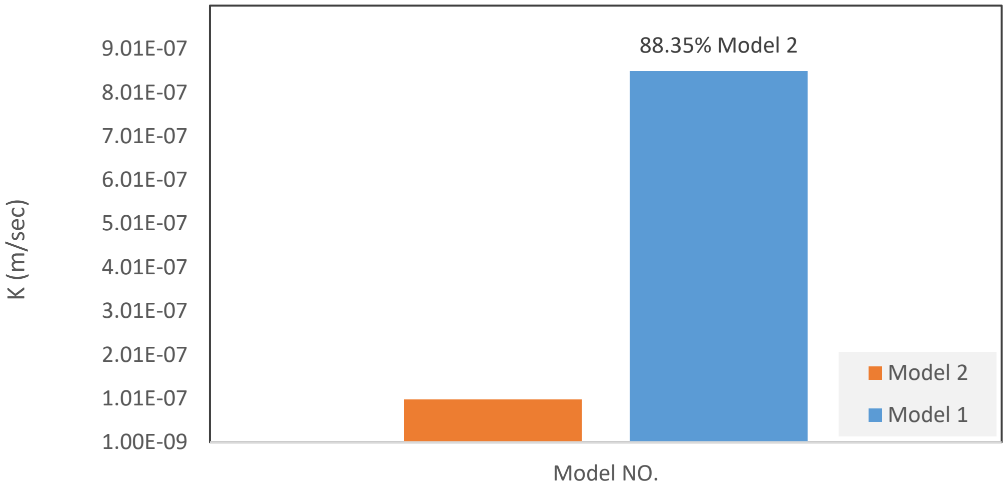

Figure 14. The hydraulic conductivity ratio between the two Models.

4.4 Physical Interpretation of the Permeability Reduction

The 88.35% decrease in filter hydraulic conductivity in summer is caused by a physical block because water goes back:

- As said by **(Huang et al., 2025),** water is forced back to the lake when the lake level drops quickly. Fine particles are carried by this backward water, and it is caught inside the filter spaces. A very bad block is made by this, and the hydraulic conductivity drops a lot.
- It is known that hot weather reduces water viscosity (which should make water flow faster by Darcy's Law). But the heavy dirt block is very strong and controls everything. Because of this, a big decrease in the hydraulic conductivity is seen at the end.

5. CONCLUSIONS

The seepage in the Al-Wand earth dam was checked using the SEEP/W program. The most important things that were found are below:

- It is confirmed that the filter in small earth dams does not stay the same all the time. It has changed a lot across seasons because the water push is different.
- The two-model idea was found to be very good. A 98% good result was reached by Model 1 (Winter), and 95% was reached by Model 2 (Summer).
- It was seen that the filter speed is made 88% slower in the summer when the water goes down fast. This is because water flows back to the lake, and the filter is blocked.
- In the future, the numbers from Model 2 (the slow filter) must be used to check if the dam is safe. If they are not used, the dam will be seen as safer than it really is during fast water drops.

In addition, the following are recommended for future studies:

- Study the particle size distribution of Material 1 to determine the precise threshold at which blockage becomes "internal corrosion."
- Use remote sensing techniques to monitor dam deformation.
- Conduct long-term laboratory vertical tests using representative filtration materials from the Alwand Dam to simulate the "blockage/unblockage" cycles observed in the field.

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Credit Authorship Contribution

Israa Abd Aljabbar Shaker: Writing the original draft, Software, Validation, and Methodology. Maysam Thamer Al-Hadidi: Results analysis and proofreading. Riyadh Z. Azzubaidi: Final scientific and proofreading review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير تقلبات مستوى المياه على خصائص الترشيح للسدود الترابية الصغيرة: سد الوند الترابي كدراسة حالة

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خلاصة

يؤثر تذبذب منسوب المياه في النهر على مدار العام على سعة تخزين المياه في هذه السدود. يبحث هذا البحث تأثير تغيرات منسوب مياه النهر على استقرار وكفاءة نظام الترشيح في سد ترابي صغير على مدى عشر سنوات. يتناول البحث تأثير تعاقب فترات الجفاف والأمطار الغزيرة على سعة تخزين المياه في السد، ويشير إلى أن الموصلية الهيدروليكية ليست ثابتة كما هو شائع في دراسات التسرب. ويركز البحث تحديدًا على سد الوند الترابي، محللًا بيانات ضغط المياه اليومية للفترة من 2015 إلى 2025 باستخدام برنامج GeoStudio (SEEP/W). أُجري البحث على أربع مراحل: جمع البيانات، والنمذجة الحاسوبية، والتحليل الموسمي، وحسابات التحقق. أظهرت هذه العملية اختلافات كبيرة بين الافتراض النظري للنفاذية المستمرة والواقع الميداني. لذا، أُجري تحليل هيدروليكي وقُسّم إلى نموذجين موسميين: الشتاء/التعبئة والصيف/انخفاض منسوب المياه. أظهرت النتائج دقةً ملحوظةً على المدى الطويل، حيث بلغت قيم كفاءة ناش–سوتكليف التراكمية 98% لنموذج الشتاء و95% لنموذج الصيف. ومن الجدير بالذكر أن الدراسة لاحظت انخفاضًا في النفاذية الفعالة عند انخفاض منسوب المياه في الصيف بنسبة تقارب 88% مقارنةً بالقيم التصميمية، وهو ما يمثل انحرافًا كبيرًا عن حدود الأمان.

الكلمات المفتاحية: بيزومترات، برنامج جيوستوديو، تحليل التسرب، سد ترابي، موديل.