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Assessing the accuracy of PHABSIM and HEC-RAS models in estimating the environmental flow of the Azad River

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ABSTRACT

There are several methods for estimating environmental flow (EF), each with its own advantages and disadvantages. This study evaluates the accuracy of two models, PHABSIM and HEC-RAS, in estimating the EF of the Azad River in Sanandaj County, Kurdistan Province. The evaluation examines three scenarios: drought, years with average rainfall, and high rainfall. For the PHABSIM model, the data utilized included water depth, water velocity, channel index, and discharge rate at cross-sections, measured at one-meter intervals from the river. In contrast, the HEC-RAS model used data on the appropriate water depth necessary for the survival of the index species. The results of the PHABSIM model for EF in September, under drought conditions and during years with average and high rainfall, showed an increasing trend. The estimated flows were 0.6 m^3/s for drought conditions, 1.5 m^3/s for average rainfall, and 2 m^3/s for high rainfall. Similarly, the HEC-RAS model exhibited an increasing trend in the same month, with estimates of 0.2 m^3/s for drought, 0.52 m^3/s for average rainfall, and 1.03 m^3/s for high rainfall. When comparing the results of the two models, it was noted that under conditions of greater water depth, where water flows into the river's side surfaces, the HEC-RAS model predicts a higher EF than the PHABSIM model.

Highlights

- The PHABSIM model predicted higher EF values than natural values during rainfall-free months.
- HEC-RAS model provides a more accurate representation of the river's extended hydrological cycle.
- The HEC-RAS model cost in predicting EF is lower compared to the PHABSIM model.

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1. Introduction

Research on estimating environmental flow (EF) began with the American Wildlife Society from 1940 to 1970. The initial focus was on improving fish habitats and ensuring that fish had the necessary flow, particularly during their migration routes. Over time, additional concerns emerged, including the protection of biological cycles. Efforts to incorporate wetlands into the EF allocation process for rivers were made only when these wetlands were linked to river ecosystems (Davis, 2005). Balancing the needs of aquatic ecosystems with other uses is crucial for many rivers worldwide (Naiman et al., 2002). EF refers to the natural volume of water that must flow through a river over a specific period to maintain, restore, or protect its ecological conditions. This includes hydrological, biological, and water quality aspects, all at a defined level (Espinoza et al., 2021; Zheng et al., 2020). When estimating the EF of rivers, a balance is established between the water requirements of the river ecosystem and the water withdrawn for economic purposes (Mlynski et al., 2020; Bejarano et al., 2019). The primary objective of estimating EF of rivers is to establish a balance between human activities and the preservation of both the river ecosystem and its dependent ecosystems, particularly in countries with limited freshwater resources (Perez-Blanco et al., 2021; Senent-Aparicio et al., 2021). Various methods exist for determining the EF. For example, Gomrokchi et al. (2019) examined the water demand of traditional gardens in Qazvin province using remote sensing technology. Their study demonstrated that if careful attention is paid to the timing of the images used, remote sensing data can effectively provide valuable information about water demand.

The Physical Habitat Simulation (PHABSIM) model is a hydrogeological tool designed to create optimal hydraulic conditions for various fish habitats. Many researchers have employed this model to estimate EF (Miao et al., 2020), identify suitable hydrological conditions for fish habitats (Weng et al., 2021), and assess the overall state of fish habitats in rivers (Knack et al., 2020). PHABSIM aims to determine the best physical habitat conditions for aquatic organisms across different river discharge levels. By integrating hydrological, hydraulic, and biological data along with information about channel shapes and riverbed characteristics, the model establishes the relationship between river discharge and the desired habitat. This understanding ultimately helps in achieving the appropriate EF for the river (Booker & Dunbar, 2004). Yi et al. (2017) utilized the PHABSIM model to examine the ecological effects of development projects on aquatic habitats. Their findings indicated that the ecological status of these habitats can be determined through either field surveys or mathematical modeling. They also emphasized that by establishing criteria for habitat suitability assessment, it becomes possible to evaluate and analyze the impact of changes in aquatic habitats on various life stages of key species. Additionally, HEC-RAS software, developed by the Hydrologic Engineering Center, can be employed to model flow in rivers. This model is both straightforward and practical. The integration of ArcGIS and HEC-RAS offers a powerful tool for river experts to make informed decisions regarding floodplain management. The HEC-RAS model is recognized as one of the simplest and most practical models for simulating various river dynamics. In a study by Kumar & Jayakumar (2021), the HEC-RAS model was utilized to analyze changes in the flow regime and EF of the Krishna River in India due to human activities. The analysis revealed that the required environmental flow for the Krishna River was not maintained approximately 43% of the time after the construction of a dam. Additionally, a study conducted by the Iran Water and Power Resources Development Company in 2019 applied the HEC-RAS model to assess the EF of the river downstream of the Ney Abad Dam in Kurdistan Province. This research determined the necessary discharge at 36 river cross-sections based on the minimum depth required to support the life of key species. The results indicated that the model tended to overestimate the EF rate during wet season scenarios compared to the actual river flow rate. Naderi et al. (2018) utilized the PHABSIM model to analyze the ecological regime of a river, specifically to estimate EF and compare these estimations with hydrological methods. They demonstrated that by assessing the needs for estimating EF in the studied river and considering its dynamic, ecological, and habitat conditions, the habitat simulation model proved to be significantly more effective than traditional hydrological approaches. They concluded that the results generated by this model are reliable and contribute to the preservation of the river's ecological environment. Studies on estimating EF require ecological data, which involves considerable time and financial investment (Gharibreza et al., 2018). One of the capabilities of the HEC-RAS model is its ability to estimate EF based on the water depth needed by indicator species (Amini & Hesami, 2017).

As a result, using the HEC-RAS model appears to be more cost-effective compared to the PHABSIM model, which necessitates additional data, including suitable water depth, water velocity, channel index, and discharge rates (Miao et al., 2020). Therefore, this study aims to examine the strengths and weaknesses of both the HEC-RAS and PHABSIM models in estimating the EF of the river downstream of the Azad Dam in Kurdistan Province, ultimately identifying the superior model for future research.

2. Materials and Methods

2.1 Study Area

The study area includes the Azad River, which flows from the Azad Dam. The Azad Dam is a medium-sized gravel dam with a clay core, located 40 km west of Sanandaj city, Kurdistan, Iran at coordinates 46° 33' latitude and 35° 21' longitude. The dam has a useful water volume of 3,241 million m^3 and a total volume of 3,300 million m^3. Its crest length measures 595 meters, and the dam stands 115 m tall. Fig. 1 shows that the river, which is associated with the dam, has a length of 6 km.

2.2 Data

The data required for this study include river cross-section, water depth, water velocity, discharge rates, channel index, and information necessary for selecting indicator species (Miao et al., 2020). Cross-section data were obtained using a surveying theodolite at a suitable, undisturbed location that is representative of other river cross-sections.

Data for the river cross-section were collected at locations where the riverbed and banks were intact, using a theodolite camera. As shown in Fig. 2, the upper part of the figure represents the cross-section of the river at a scale of 1:200. The second row, from left to right, displays the distance from the starting point of the survey to the end point of the river surface, which measures 24 m in this figure. The third row indicates the depth of the river at various points, revealing that the deepest part of the river is 2.5 m. Water depth and velocity data were collected at one-meter intervals across the river cross-section using a Molina. This information was then utilized to estimate the volume of water flowing in the river. Sampling for this study began in the autumn of 2018 and continued monthly until autumn 2019. The index fish species were identified based on eight criteria, which included international conservation value, conservation value in Iran, distribution in the basin, sport fishing value, economic value, ecological value, and whether the species is native or non-native (Bovee, 1982).

Fig. 1 Geographical position of the study area

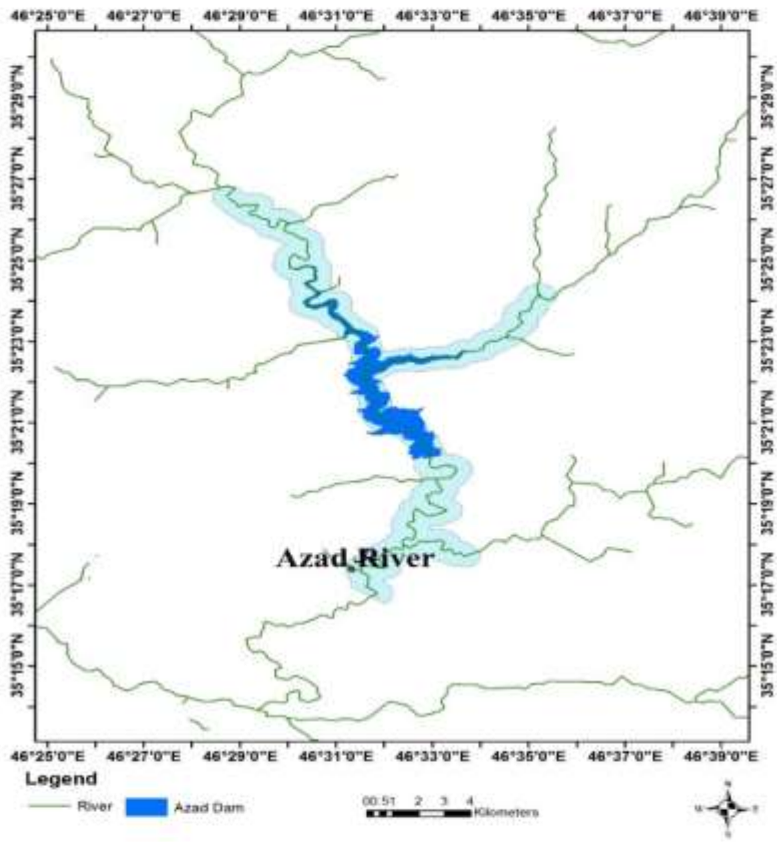
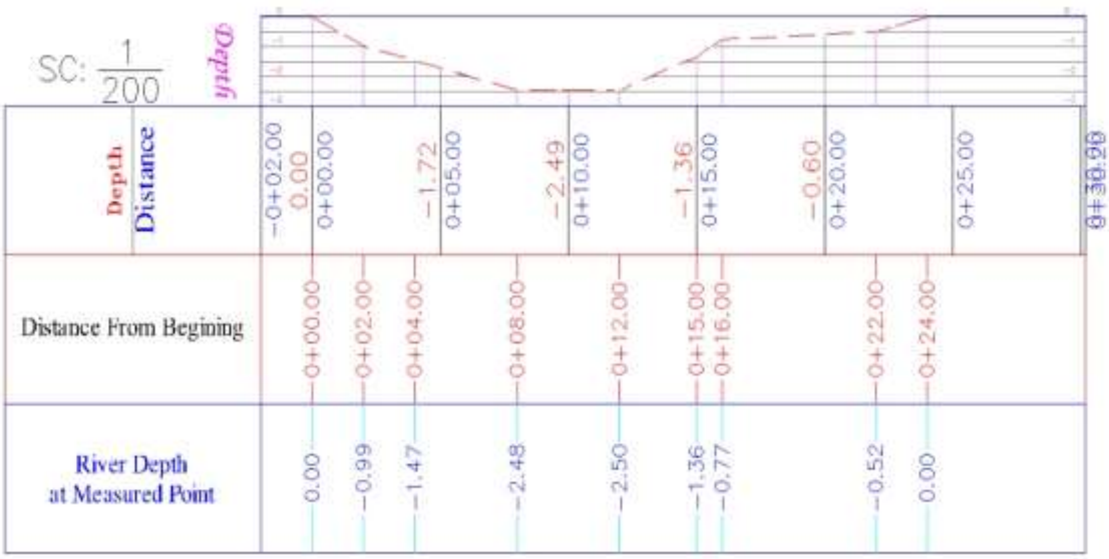


Fig. 2 A sample of cross-sections used in PHABSIM and HEC-RAS models



Conservation value in Iran is categorized into three levels according to Resolution No. 168 dated March 6, 1999, from the Supreme Council of the Environmental Protection Organization for aquatic animals. The classification is as follows:

- Level A: Species at risk of extinction (score = 3)
- Level B: Protected species (score = 2)
- Level C: Non-protected species (score = 1)

The scoring for the remaining indicators was conducted by faculty members from the Fisheries Department at the University of Kurdistan and experts from the Kurdistan Provincial Fisheries Department. The average score for each indicator was calculated for each species, and the final score for each species was determined by summing the scores of all indicators. Table 1 shows that the Barbus lacerta species was chosen as the indicator species, as its ecological needs effectively reflect the ecological requirements of the ecosystem.

Table 1 Criteria and their value in indicator species selection

Species Name	Alburnus mossulensis	Capoeta trutta	Carassius auratus	Barbus lacerta	Rhinogobius similis
International conservation value	3	1	1	1	1
Conservation value in Iran	1	1	1	3	1
Distribution in the basin	1	1	1	3	1
Distribution in the region and world	1	1	1	1	1
Sport fishing value	5	5	1	5	1
Economic value	2	4	1	3	1
Ecological value	1	1	1	1	1
Species is native or non-native	+	+	-	+	-
Total	14	14	-6	17	-6

The channel index variable is a crucial parameter used in modeling the EF of rivers. To determine this index, three samples were collected from the bedrock at the river cross-section. In the laboratory, the diameters of all rocks, rubble, sand, and gravel within each sample were measured using a sieve, caliper, and ruler. The diameter ranges were then expressed in percentage terms. The channel index was estimated based on these percentage ranges and calculated using Table 2 for the Azad River.

Table 2 Channel index codes based on floor materials (Platts et al., 1983)

Channel Index	1	2	3	4	5	6	7	8
Bed material size (mm)	Organic materials	Clay	Silt 0. 62<	Sand 0.2-0.62	Gravel 2-64	Rubble 64-250	Boulders 250-4000	Rocky bottom

Information about channel index and previous studies conducted in the rivers surrounding the Azad River were utilized to determine the Manning coefficient, also known as the roughness coefficient, for this river, as referenced in. Ultimately, a roughness coefficient of 0.048 was obtained for use in the HEC-RAS model.

2.3 EF estimation modeling

2.3.1 PHABSIM model

This method evaluates habitat suitability in relation to changes in water flow (Dongkyun et al., 2017). Introduced by the United States Wildlife Service in 1970, it aims to assess the water supply status of habitats in critical sections of rivers (Habibi Alagoz, 2016). This approach combines hydraulic and habitat models, linking flow conditions to the physical habitat suitability for target species within the river ecosystem. To enhance the accuracy of the habitat simulation model, it is important to select appropriate aquatic indicator species. The presence of indicator species should depend on environmental changes (Bovee, 1982). In habitat simulation methods, the physical conditions of a river are taken into account, using hydraulic factors such as depth and flow velocity to identify the optimal river conditions for one or more selected species. This assessment helps to evaluate the EF. The most notable method in this category is BPHABSIM (USGS, 2012), which comprises three hydrological modules, a hydraulic module, and a habitat module. Initially, the model takes in hydraulic data related to the river, including discharge, depth, velocity, and the geometry of the river sections. Following this, the hydraulic module of the software simulates the flow parameters for the specified discharges. The hydraulic module employs a one-dimensional approach, while software like River 2D incorporates the concept of two-dimensional average depth in hydraulic simulation. This means that, in addition to accounting for downstream longitudinal variations, it also takes into consideration transverse changes. In one-dimensional simulations, the number of sections is determined by the morphological changes of the riverbed. Moreover, this method assumes a uniform waterway. Typically, one-dimensional models feature between 6 to 10 sections for simple flows and 18 to 20 sections for more complex flows (Jowett et al., 2008). The accuracy of the data in these sections directly impacts the quality of the simulation results (Booker & Dunbar, 2004). In summary, each section of this method is divided into multiple cells. To derive quantitative outcomes from a physical habitat simulation model, a composite suitability index (CSI) must be calculated. This index combines the suitability values of various habitat variables, including velocity, depth, and substrate type. Suitability functions are then compared to assess the degree of suitability for each cell, taking into account the current conditions of velocity, depth, and substrate. Ultimately, the scores from each parameter are aggregated to establish a composite suitability index for each cell within each section. The final index utilized in determining EF is known as the Weighted Usable Area (WUA). This index is calculated by multiplying the Habitat Suitability Index (HSI) for each cell by the corresponding available surface area. The total WUA value illustrates the relationship between habitat depletion and the quality and quantity of a microhabitat. By converting this index into a graph, one can effectively examine the changes in available habitat as depletion occurs. It is important to acknowledge that there has been some criticism regarding the correlation between fish biomass and habitat availability or WUA (Conder & Anear, 1987). Nonetheless, some studies support a positive relationship between these variables (Jowett & Davey, 2007).

2.3.2 HEC-RAS model

HEC-RAS is a mathematical software developed by the United States Army Corps of Engineers (Ongdas et al., 2020). HEC-RAS models the hydraulics of water flow through natural rivers and various channels. It is primarily designed to utilize unstructured computational grids but also accommodates structured grids (Mustafa & Szydlowski, 2021). HEC-RAS is widely employed for solving equations related to one-dimensional (1D) steady and unsteady flow, conducting river hydraulic calculations, managing two-dimensional (2D) unsteady flow, modeling sediment transport, and analyzing water quality (Leon & Goodell, 2016). One-dimensional models are frequently employed to estimate flow velocity and water levels. In these models, rivers are typically represented as a linear feature, with the channel shape characterized at each node along the river line. In contrast, two-dimensional models depict the river as a network of polygonal cells, which effectively represent the topography of the primary river channel (Pinos & Timbe, 2019).

HEC-RAS calculates water levels by solving the energy equation using a standard step-by-step approach (Shahrokhnia et al., 2008). The model consists of individual units known as grid cells, which contain elevation data and roughness values at each grid location. Additionally, HEC-RAS enables the computation of hydraulic properties, such as cross-sectional area and wetted area, at any specified flow depth (Shrestha et al., 2020).

3. Results and Discussion

3.1 PHABSIM model results

The PHABSIM model generates a total of 36 output shapes for estimating EF over 12 months across three scenarios: drought, average rainfall years, and high rainfall years. For this report, only the output shapes for two specific months are presented: September, representing low river water conditions, and April, representing high river water conditions. Results for the remaining months can be found in Table 3. Fig. 3a presents the results of the PHABSIM model, illustrating the WUA in September, typically a low water month, under drought conditions, where the EF is represented as approximately 4900. In this context, the EF is measured at 0.6 m³/s. Fig. 3b shows the suitability of various sections of the Azad River, as determined by the EF estimates from the PHABSIM model for September in the drought scenario. It indicates that at least 40 percent of the river's cross-section provides a suitable habitat for the target fish species, while the remaining sections exhibit lower ecological quality for sustaining these species.

The EF and WUA rates for the Azad River during the years with average rainfall scenario in September are illustrated in Fig. 3c. In this figure, the WUA rate is approximately 14500, while the EF is set at 1.5 m³/s. Fig. 3d highlights the desirability of various sections of the Azad River in relation to this EF. The impact of river habitat on this ecological flow is significant, revealing that around 50 percent of the Azad River exhibits the highest quality, whereas the remaining sections display lower quality regarding the estimated ecological requirements necessary for the survival of the index species. In the years with the high rainfall scenario depicted in Fig. 3e, the EF for the Azad River in September is 2 m³/s. Fig. 3f illustrates the desirability of various sections of the Azad River concerning this EF, as determined by the PHABSIM model. Notably, approximately 80 percent of the river's segments are rated as having the highest quality, while the remaining sections exhibit lower quality in relation to the ecological needs essential for the survival of the index species.

3.٢PHABSIM model

Fig. 4a shows the results of the PHABSIM model in April (the month of high water) in the drought scenario. In this figure, the WUA rate is approximately 16,500, and the EF rate is 1.2 m³/s. With the increase in the water volume in the river, the WUA rate has shown very little change towards increasing. Fig. 4b illustrates the suitability of various sections of the free river under a water flow of 1.2 m³/s, as provided by the PHABSIM model during the drought scenario in April. In this figure, it is shown that 60 percent of the river's sections demonstrate a high suitability degree for the index species, primarily located on the right side of the river. The remaining sections exhibit medium to high suitability, indicating that if the estimated EF for the river is met, 60 percent of the habitats will be preserved, while the quality of the remaining habitats may slightly decline for the index species.

Fig. 4c illustrates the EF rate in the Azad River during an average water year scenario in April, as predicted by the PHABSIM model. The model output indicates a flow rate of 2.4 m³/s. The WUA rate presented in this figure is approximately 22,250, which marks a significant increase compared to the drought period rate of 16,500 recorded during the same timeframe. Fig. 4d depicts the habitat suitability of the Azad River under the specified EF. As shown in this figure, one section of the river exhibits maximum suitability, while the remaining areas demonstrate medium to high suitability for the index species at this flow rate. Fig. 4e illustrates the EF of the Azad River in April during year with a high rainfall scenario. According to this figure, the EF measures 2.3 m³/s. Under these conditions, the WUA is approximately 22,600, which represents a slight increase compared to the average rainfall year, where the WUA was 22,250. Fig. 4f depicts the suitability of different sections of the Azad River during a year with high rainfall. At this flow rate, most areas of the river exhibit moderate to high conditions for the survival of the indicator species, similar to the habitat conditions observed in the average rainfall year. However, the key difference is that in the average rainfall year, the total WUA shows a smaller increase.

Fig. 3 PHABSIM model in September in AZAD river: a) amount of WUA in the drought scenario, b) desirability of different parts of the river in the drought scenario, c) amount of WUA in the year with average rainfall scenario, d) desirability of different parts of the river in the year with average rainfall scenario, e) amount of WUA in the year with high rainfall scenario, f) desirability of different parts of the river in the year with high rainfall scenario.

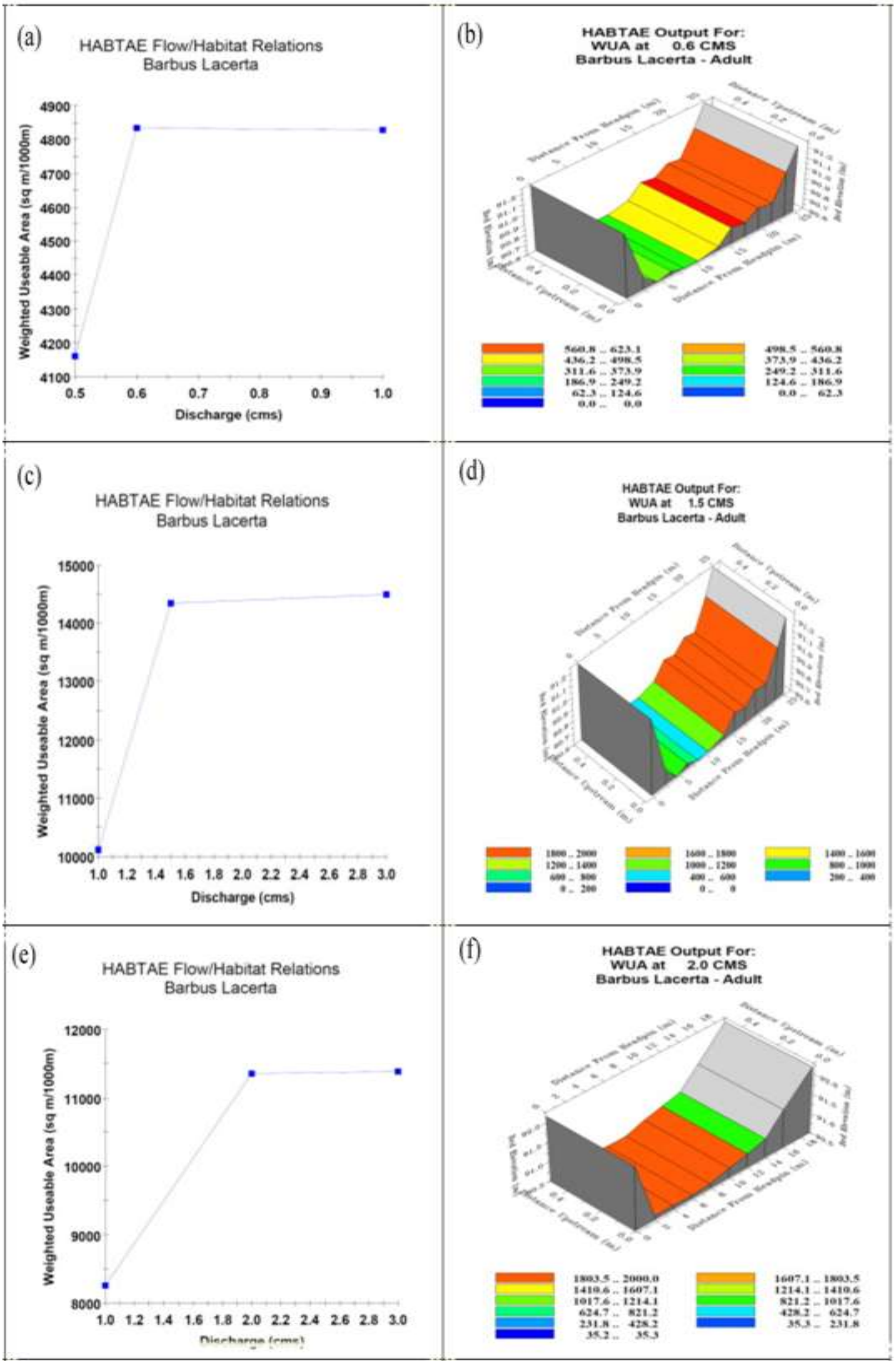


Fig. 4 PHABSIM model in April in AZAD river: a) amount of WUA in the drought scenario, b) desirability of different parts of the river in the drought scenario, c) amount of WUA in the year with average rainfall scenario, d) desirability of different parts of the river in the year with average rainfall scenario, e) amount of WUA in the year with high rainfall scenario, and f) desirability of different parts of the river in the year with high rainfall scenario.

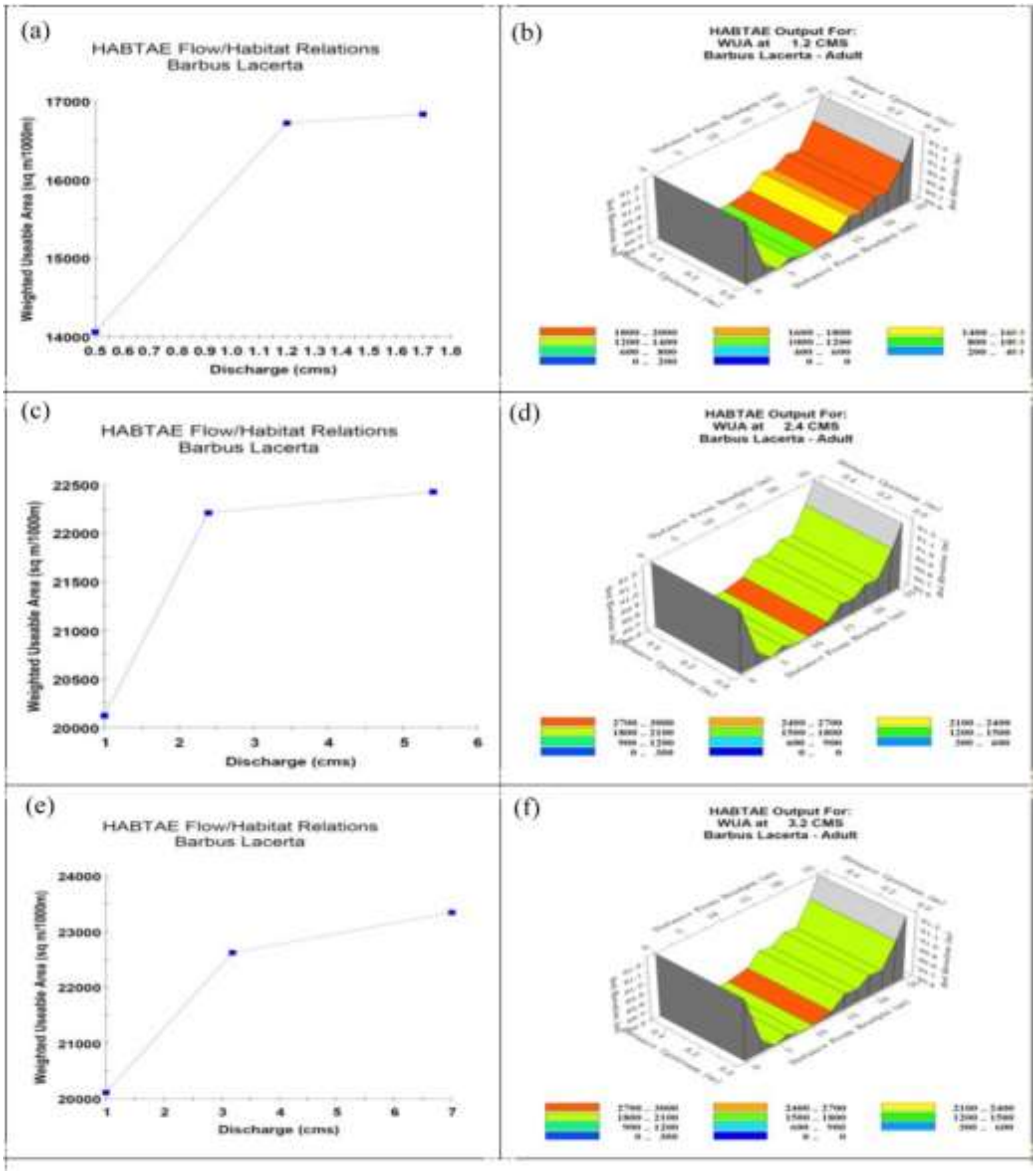


Table 3 The amount of EF in three scenarios of drought, years with average rainfall and high rainfall in the Azad River, outputted of PHABSIM model

Month	EF (m^3/s)		
	Drought	Average rainfall	High rainfall
January	0.4	1.2	1.6
February	0.8	1.6	2.2
March	0.6	1.6	2.1
April	1.2	2.4	3.2
May	1.4	2.0	3.0
June	1.1	2.0	3.0
July	0.9	1.4	2.8
Aguste	0.8	1.2	2.0
September	0.5	1.0	1.5
September	0.6	1.5	2.0
November	0.6	1.4	2.5
December	0.7	1.5	2.5

3.1.3 PHABSIM model

Table 3 shows that in the drought scenario, the highest EF recorded in May is 1.4 m^3/s, while the lowest EF in the same scenario occurs in September at 0.5 m^3/s. During a year with average rainfall, the lowest EF is also in September, measured at 1 m^3/s, and the highest EF in this scenario occurs in April at 2.4 m^3/s. For a year with high rainfall, the highest EF is again in April at 2.3 m^3/s, with the lowest EF remaining similar to the previous two scenarios, occurring in September at 1.5 m^3/s.

3.2 HEC-RAS Model Results

3.2.1 HEC-RAS

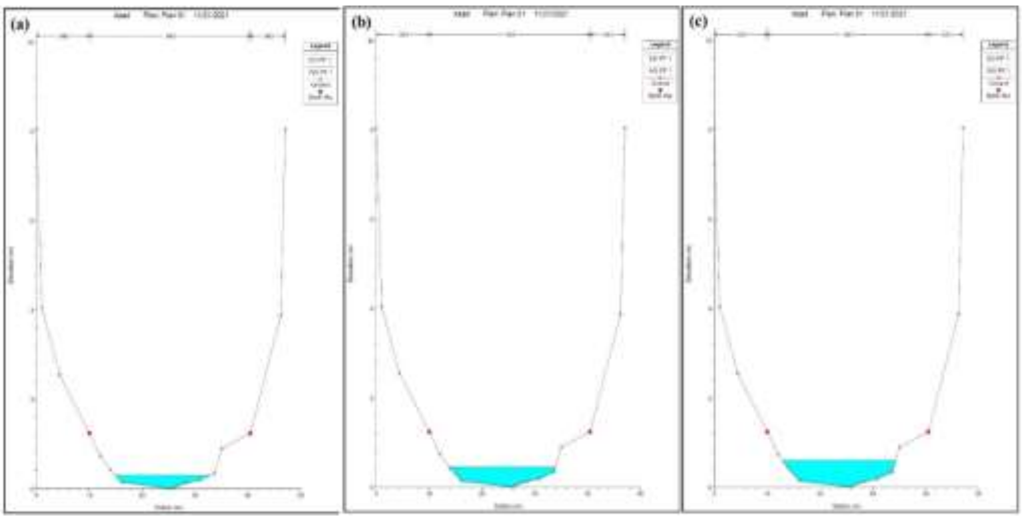
In the HEC-RAS model, a significant number of output shapes were generated over a 12-month period, across three scenarios: drought, years with average rainfall, and high rainfall. This study presents the output shapes for two specific months, aligning with the findings of the PHABSIM model—September, representing low water conditions, and April, reflecting high water conditions. Table 4 provides the required depths for the optimal living conditions of the index species necessary for modeling in HEC-RAS. Fig. 5a presents the EF for September under a drought scenario, as derived from the HEC-RAS model implementation. This figure illustrates the river's cross-section with water flowing at a depth of 0.3 m. In this drought scenario, maintaining a water flow depth of 0.3 m at this cross-section requires a flow volume of 0.2 m^3/s, which represents the EF for the river in this context.

If this EF criterion is achieved, the flowing water will exhibit a velocity of 0.06 m/s, a water level of 18.11 m, a cross-sectional area of 3.42 m^2, and a wetted area of 18.13 m^2. As indicated in Table 4, during a year characterized by year with an average rainfall scenario, a volume of water with a depth of 0.45 m must flow through the river to satisfy the minimum EF requirement. To maintain a flow depth of 0.45 m at this particular cross-sectional area, the water must have a volume of 0.52 m^3/s. Fig. 5b illustrates the EF for this river under the average rainfall scenario. If this EF is achieved, the water will flow at a velocity of 0.08 m/s, with a river level of 20.15 m, a cross-sectional area of 6.23 m^2, and a wetted area of 20.20 m^2. As shown in Fig. 5c, the estimated EF during wet years is higher than that for both average rainfall and drought scenarios.

Table 4 Suitable water depths for the indicator species in three scenarios

Sampling Date	Suitable Water Depths		
	Drought	Average rainfall	High rainfall
January	0.20	0.35	0.50
February	0.34	0.45	0.66
March	0.35	0.37	0.40
April	0.34	0.77	1.20
May	0.60	0.80	1.00
June	0.35	0.66	0.90
July	0.47	0.55	0.80
Aguste	0.20	0.45	0.80
September	0.15	0.33	0.50
September	0.30	0.45	0.60
November	0.27	0.40	0.50
December	0.30	0.35	0.40

Fig. 5 Results of HEC-RAS model in September (low water level in the river): a) drought scenario, b) year with average rainfall scenario, c) year with high rainfall scenario

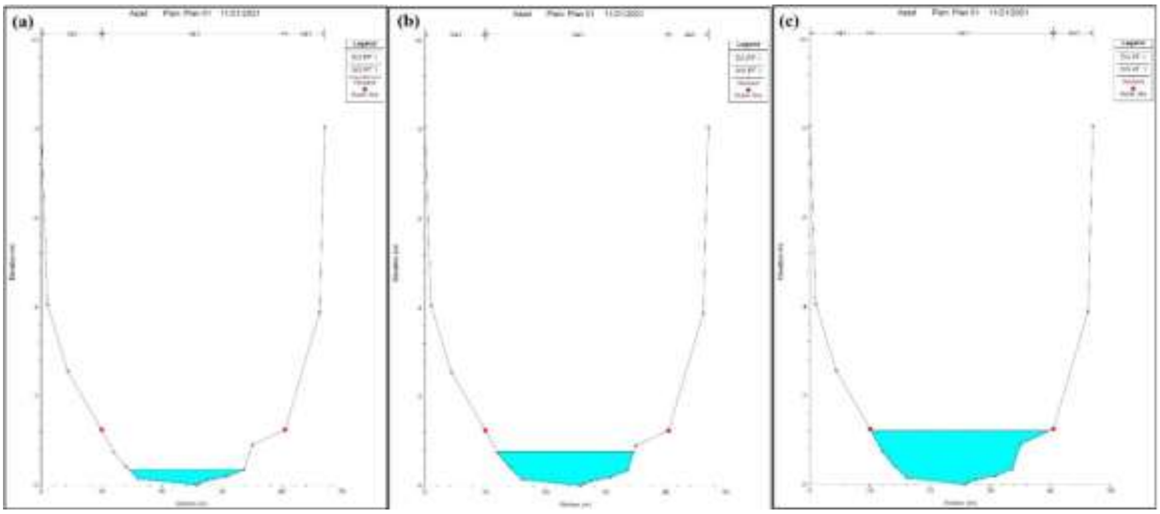


According to Table 4, the EF in the river must reach a depth of 0.6 m. To achieve this depth, the water needs to flow at a volume of 1.03 m³/s, which represents the EF for this river during a year with high rainfall. When this EF is attained, the flowing water will exhibit a velocity of 0.11 m/s, the water level in the river will rise to 21.47 m, the cross-sectional area will be 9.41 m², and the wetted area will measure 21.56 m.

3.2.2 HEC-RAS Model results in April in three scenarios

The results of the HEC-RAS model in three scenarios for the month of April are shown in Fig. 6. Fig. 6a shows the level and depth of water flowing in the Azad River in the month of April in the drought scenario. When comparing the water flow in September under the drought scenario illustrated in Fig. 5a, it is evident that the EF in April is significantly higher. This increase is necessary to provide the appropriate water depth for sustaining habitats both in and along the river. Specifically, in April's drought scenario, a water depth of 0.34 m is required to meet the EF. For water to flow at a depth of 0.34 m in this river cross-section, a volume of 0.27 m³/s is required. At this EF, the water will have a velocity of 0.07 m/s, the river's water level will be at 19.12 m, the cross-sectional area will measure 14.4 m², and the wetted area will be 14.19 m². Fig. 6b illustrates the water level and depth in the Azad River during April under an average rainfall scenario. According to Table 4, the required water depth is 0.77 m, necessitating a flow volume of 1.8 m³/s. At this EF, the flowing water's velocity will increase to 0.14 m/s, with the river level rising to 22.81 m. Here, the cross-sectional area will be 13.08 m², while the wetted area will expand to 22.95 m². Fig. 6c shows the EF during April in a year with a high rainfall scenario. This figure clearly indicates that the estimated EF in this scenario exceeds that of both average rainfall and drought scenarios. Table 4 presents that the minimum water depth required to achieve this EF is 1.2 m. To sustain this water depth in the river cross-section, a flow volume of 5 m³/s is necessary. At this EF, the flowing water exhibits a velocity of 0.21 m/s, with the river's water level at 29.56 m. The cross-sectional area measures 24.06 m², while the wetted area is 29.78 m.

Fig. 6 Results of HEC-RAS model in April (high water level in the river): a) drought scenario, b) year with average rainfall scenario, and c) year with high rainfall scenario



3.2.3 HEC-RAS model results over one year in three scenarios

As shown in Table 5, the highest EF observed in the drought scenario during May is 1.03 m³/s. In contrast, the lowest EF in this scenario occurs in September, with a value of 0.04 m³/s. In the average rainfall scenario, the lowest EF also pertains to September, measuring 0.25 m³/s, while the highest demand in this scenario is noted in April, reaching 2 m³/s. In the high rainfall scenario, the peak EF for April is 3.35 m³/s, while the lowest EF, consistent with the earlier scenarios, remains in September at 0.4 m³/s. The results of the PHABSIM model, which estimate the EF for September, demonstrate a logical trend. The EF increases from the drought scenario to the average rainfall and high rainfall year scenarios, recorded at 0.6 m³/s, 1.5 m³/s, and 2 m³/s, respectively. However, it is noteworthy that the WUA for the high rainfall scenario is lower than that for the average rainfall year. This anomaly arises from the different cross-sections used in the EF estimations. For the drought and average rainfall scenarios, a single cross-section was employed, whereas a distinct cross-section was utilized for the high rainfall scenario. The PHABSIM model calculates the WUA based on the cross-section's width, which, in the case of the high rainfall scenario, is smaller than that of the average rainfall and drought scenarios. The necessity for varying cross-sections across different scenarios stems from the differing requirements for depth and water velocity, which may not align consistently with the hydrological data at a specific point.

Table 5 The amount of EF in three scenarios of drought, years with average rainfall, and high rainfall in the Azad River, outputted of the HEC-RAS model.

Month	EF (m^3/s)		
	Drought	Average rainfall	High rainfall
January	0.07	0.29	0.67
February	0.27	0.52	1.28
March	0.29	0.37	0.40
April	0.27	1.80	5.00
May	1.03	2.00	3.35
June	0.29	1.28	2.63
July	0.57	0.85	2.00
Aguste	0.07	0.52	2.00
September	0.04	0.25	0.40
September	0.20	0.52	1.03
November	0.15	0.40	0.67
December	0.20	0.29	0.40

The results from the PHABSIM model for April demonstrate a reasonable capacity to estimate the EF across different rainfall scenarios: drought, average rainfall, and high rainfall. The EF values observed are 1.2 m^3/s, 2.4 m^3/s, and 3.2 m^3/s, respectively, indicating an upward trend. Notably, there is a difference of 0.8 m^3/s in EF between the average rainfall and high rainfall scenarios. Although the same cross-section was utilized for both scenarios, the WUA reported for the average rainfall year scenario (22,250) shows a slight increase of 250 when compared to the high rainfall scenario (22,500). This slight variation may be attributed to the fact that the EF indicated by the model in the average rainfall year scenario is adequate for maintaining river-dependent habitats under favorable conditions. Although the required depth and velocity have increased in the high rainfall scenario compared to the average rainfall scenario, the parameters established in the average rainfall scenario have almost reached the maximum WUA for the river. Consequently, the increase in EF during the high rainfall scenario has only resulted in a minor increase in WUA. Therefore, it can be concluded that the EF in the average rainfall year is sufficiently robust to support the ecosystems reliant on the river during high rainfall conditions.

The EF output from the HEC-RAS model is expected to increase exponentially, particularly during the high rainfall events of April and May. During this period, the results from the HEC-RAS model exceeded those of the PHABSIM model. This trend aligns with findings from a study conducted by the Iranian Water and Power Resources Development Company, which utilized the HEC-RAS model to determine the EF of the river downstream of the Niabad Dam. The results revealed that this model tends to estimate a higher EF rate compared to the actual river flow rate in high rainfall scenarios. Conversely, the PHABSIM model demonstrates fewer drawbacks in calculating the EF when compared to the HEC-RAS model. This observation is supported by Naderi et al. (2018), who found that the PHABSIM model is significantly more accurate than hydrological methods for determining EF.

The findings of the current study indicate that both models possess distinct advantages and disadvantages, which could either challenge or support their application. This can be referenced in light of the results from the research conducted by Kumar & Jayakumar (2021) and Caiola et al. (2014). In both studies, the EF was calculated using a variety of ecological models, while water velocity and depth—crucial factors for the survival of index species—were measured using the HEC-RAS model. Both studies emphasize the necessity of employing hydrological models, such as HEC-RAS, in conjunction with ecological models for the accurate estimation of EF.

4. Conclusion

The estimation of EF in the HEC-RAS model relies solely on the specified water depth data. When comparing the results of the HEC-RAS model to those of the PHABSIM model, it is evident that the HEC-RAS model tends to estimate EF at lower values than the PHABSIM model. The findings of this research can be summarized as follows:

1. In the PHABSIM model, any section of the river that meets the target species' requirements in terms of depth, velocity, and channel index is classified as suitable habitat.

2. Unnatural River flow, like that from dam foothills, can lead to higher EF values calculated by the PHABSIM model in August and September, compared to the natural state when river flow is typically lower.

3. The results of the HEC-RAS model and the PHABSIM model in predicting EF for the September drought scenario were 0.04 m^3/s and 0.5 m^3/s, respectively. This indicates that the HEC-RAS model's results are more aligned with the long-term hydrological cycle of the river.

4. The HEC-RAS model has the advantage of requiring less data than the PHABSIM model, resulting in significantly lower implementation costs.

Statements and Declarations

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Data availability

The data for this study were obtained from the research project of the University of Kurdistan, which can be presented after obtaining permission from the Iranian Water and Power Resources Development Company.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

A. Baziar: Data analysis, Modeling; and J. Amanollahi: Research guide, Modeling, Results analysis, Revision of the manuscript, and Editing.

AI Use Declaration

This study did not incorporate artificial intelligence techniques; instead, all analyses and optimizations were conducted using conventional and widely accepted analytical methods.

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