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Research on Well Selection Method for Intermittent Pumping in Oil Wells Based on the Analytic Network Process and Fuzzy Logic

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Abstract: In the later stages of oilfield development, the decline in oil well production and the increase in development costs, attributed to issues such as insufficient liquid supply, necessitate the implementation of intermittent pumping measures. However, current methods for selecting these wells lack comprehensiveness in the decision-making process. This article proposes a novel method for selecting intermittent pumping wells utilizing the analytic network process (ANP) and fuzzy logic. Initial surveys identified the main factors influencing intermittent pumping effectiveness. The ANP was employed to screen and integrate six core factors, including submergence depth and water cut. Subsequently, a fuzzy-logic-based model was developed, incorporating trapezoidal and rectangular membership functions to establish detailed correlations among the factors. The model's efficacy was validated and tested using real-world data from the oilfield. Results indicate that the model's assessments of intermittent pumping wells align closely with professional engineering judgments. This approach not only provides clear guidance for well selection but also demonstrates high scalability and adaptability across different oilfields by adjusting membership functions, thereby showcasing significant practical value.

Keywords: fuzzy logic; analytic network process; oil pumping well; intermittent pumping; well selection

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1. Introduction

Long-term production has led to the depletion of formation energy, resulting in insufficient liquid supply to the oil wells. Continuous production under such conditions would reduce efficiency and damage equipment. To address this issue, intermittent pumping can be employed, allowing for planned extraction to control the dynamic fluid level and enhance production efficiency. However, given the complexity of geology and reservoirs, not all oil wells with insufficient liquid supply are suitable for intermittent pumping strategies. Accurately selecting oil wells suitable for intermittent pumping is crucial for reducing costs and improving benefits. Nevertheless, in current research, there is no systematic well selection method for the decision-making process of selecting intermittent pumping wells [1,2].

Numerous studies have investigated the factors influencing the effectiveness of intermittent pumping. Wei emphasized the importance of the pump condition in oil extraction, particularly in the specific development environment of the oilfield [3]. In experiments exploring and optimizing the intermittent pumping cycle for oil wells, Zhu not only analyzed the permeability of the oil layer, the connectivity of surrounding water wells, submergence death, production and pressure trends, and the mechanical parameters of the pumping unit but also closely monitored key indicators such as the volume of fluid produced, oil output, and the efficiency of the oil pumps, using these as a basis for experimental design [4]. Si, in the process of selecting wells for intermittent pumping, added an evaluation of well permeability, further refining the criteria for well selection [5]. Building on previous work,

Tian emphasized the consideration of effective reservoir thickness, providing a more precise geological basis for intermittent pumping strategies [6]. Qin incorporated an assessment of reservoir fluid supply capacity into field trials of intermittent pumping, enhancing the accuracy of the experimental results [7]. Guo et al., provide a more comprehensive analysis of production conditions for the formulation of intermittent pumping strategies, starting from the liquid production rate and sand production [8]. Liu, building on previous research, further expands the scope of consideration, incorporating reservoir conditions as one of the analysis elements, and selects three different types of oil wells for comparative analysis, enriching the diversity and practicality of the experiments [9]. Pu et al., delve into the phenomenon of oil well wax deposition and the potential impact of intermittent pumping operations on production, offering new perspectives and strategies for oil well management and maintenance [10]. Finally, scholars such as Yu comprehensively consider the degree of pump filling, water cut, and the specific impact of intermittent pumping operations on production, constructing a more comprehensive and practical oil well intermittent pumping evaluation system [11]. These studies not only reflect the profound understanding and unique insights of scholars on oil well intermittent pumping technology but also provide valuable references and guidance for subsequent practices. However, existing studies have limitations in the well selection factors and the adaptability of the methods. While researchers have considered diverse factors, some are affected by difficulties in data acquisition, which lower the practicality of the methods. Additionally, most studies lack an analysis of the interactions between the various influencing factors, which may lead to less accurate assessments of well selection for intermittent pumping. Therefore, it is necessary to simplify the well selection factors, highlight the key factors, and conduct a deeper analysis of the interactions between the factors to establish a more representative evaluation model.

The preceding discussion reveals that a thorough analysis of intermittent pumping effectiveness necessitates considering numerous complex and interwoven factors. These factors, summarized from the above, include permeability, effective net sand, reservoir conditions, connectivity with surrounding water wells, injection capacity of surrounding water injection wells, sand particle diameter, sand production, crude oil viscosity, liquid production rate, oil production rate, water cut, gas–liquid ratio, production and pressure trends, fluid supply, pump condition, pump efficiency, pump fill degree, wax deposition, impact of intermittent production on production rate, submergence depth, pump setting depth, stroke, strokes per minute, artificial lift parameter adjustments, well deviation, and rate of overall angle change. While all these factors can serve as initial considerations, due to the inherent complexity of oil well systems, they are not mutually exclusive. Interdependencies exist between these factors, and their influence on intermittent pumping well selection decisions varies both in nature and magnitude. Consequently, a suitable methodology is required to calculate and screen these factors based on their degree of impact.

For the calculation of the degree of impact of factors, the commonly used method is the analytic hierarchy process (AHP). This method effectively helps in analyzing and assessing the relative importance of different factors. However, due to the complex interdependencies and influences among the factors affecting intermittent pumping effectiveness, the AHP is not suitable. To address this, this study adopts a more appropriate scientific decision-making method for complex structures: the analytic network process (ANP). The ANP has been widely applied in the energy sector. Hasanzadeh et al., utilized the ANP for oil terminal site selection, comprehensively considering the interdependencies between social, environmental, and other factors during the selection process [12]. Liu et al., employed the ANP to calculate reasonable weights for each criterion when conducting individual and overall risk assessments for ultra-deep scientific drilling projects using criteria such as probability and severity [13]. Mirderikvand et al., when establishing a quantitative barrier-risk-based well blowout evaluation model for drilling, applied the ANP to comprehensively calculate the weights of well barrier performance indicators [14]. Melani et al., when performing criticality maintenance for coal-fired power plants, considering

that each component failure affects system performance to some extent, utilized the ANP for comprehensive risk assessment of maintenance costs, repairability, and other related risks, thereby prioritizing component criticality to prevent asset performance losses [15]. Given the effective application of the ANP in the energy sector, this study introduced the ANP to the intermittent pumping well selection decision-making problem. This allows for effective consideration of the influence of various factors and their interrelationships on well selection for intermittent pumping, enabling a more comprehensive evaluation.

However, the selection of intermittent pumping wells is essentially a fuzzy and multi-dimensional decision-making issue, requiring comprehensive consideration of multiple intertwined and deeply influential key factors such as reservoir characteristics, fluid properties, and production conditions. The complex combinations and dynamic interactions among these factors significantly increase the difficulty of evaluating intermittent pumping well selection, making it challenging to achieve precise and comprehensive judgments based solely on single or simple evaluation criteria. Therefore, this study introduces the concept of fuzzy logic, using fuzzy concepts and ranges to represent uncertain factors, and employing membership functions and fuzzy sets to handle fuzzy and uncertain information. By utilizing fuzzy logic to combine multiple factors and achieve overlapping feature spaces, it is possible to conduct a comprehensive and objective analysis and evaluation of the impact of intermittent pumping effect factors on well selection.

Despite the lack of reported applications of fuzzy logic in the field of intermittent well selection, fuzzy logic has been widely applied to similar problems in other areas of petroleum engineering. Ilyas et al., employed fuzzy logic to optimize crude oil transportation routes considering factors such as time, financial expenditure, and energy consumption, thereby enhancing transportation efficiency and addressing the uncertainties and imprecisions in the decision-making process for crude oil transportation routes [16]. Biezma et al., utilized a fuzzy logic system to analyze six soil characteristics, including water content and pH, to estimate the corrosivity of soil on oil and gas pipelines, reducing the number of field tests compared to traditional methods [17]. Roisenberg et al., used fuzzy logic to calculate the favorability and risk of six geological factors, including source rocks, reservoir rocks, and seal rocks, for risk assessment in oil exploration, achieving successful application [18]. Chowdhury et al., developed a model based on fuzzy logic to estimate the downhole cutting concentration, considering the complex influence of factors such as flow rate, drilling speed, and well type, which provided more accurate estimates compared to dimensional analysis and critical drilling fluid velocity concept models [19]. Hassan et al., applied fuzzy logic theory to calculate the relative importance of fault probability, severity, and detection, offering a more effective method for identifying hazards and analyzing risks in product pipeline systems in regions with limited or unreliable data [20].

The above research cases from other areas of the petroleum industry demonstrate that the application of fuzzy logic methods not only improves the accuracy of various tasks but also significantly enhances the scientific and effective nature of decision-making. As technology continues to advance and applications expand, fuzzy logic is expected to play an increasingly important role in the petroleum industry, driving the intelligent and efficient development of oil exploration, development, production, and management.

Based on the above analysis, this study considered introducing the analytic network process (ANP) and fuzzy logic methods to construct a systematic intermittent pumping well selection method. Firstly, through relevant literature research and oilfield data analysis, potential key factors affecting the effectiveness of oil well intermittent pumping were identified and organized. Secondly, the ANP was utilized to calculate the index weights of each factor, selecting those with higher weights as the considerations for establishing the intermittent pumping well selection model. On this basis, a comprehensive intermittent pumping well decision-making model was constructed through fuzzy logic, enabling multi-factor decision-making for well selection. This model effectively addresses the complex decision-making environment characterized by multiple variables and uncertainties, ensuring precise decision-making for intermittent pumping well selection based on a com-

prehensive consideration of multiple factors. Finally, the method was applied in field trials. The trial results demonstrate that the method possesses high adaptability and scalability, capable of adjusting parameters according to specific conditions of different regions and oilfields (such as reservoir characteristics, fluid properties, production parameters, etc.), to meet diverse well selection needs.

The structure of this paper is divided into six sections. Section 2 introduces the screening of factors influencing the effectiveness of intermittent well operations using the analytic network process (ANP). Section 3 presents the concept and process of fuzzy logic. Section 4 focuses on the development of the intermittent well selection method based on fuzzy logic. Section 5 emphasizes the application of the intermittent well selection method and provides case studies. Finally, Section 6 offers a summary and analysis of the entire paper.

2. Screening Factors Influencing the Effectiveness of Intermittent Well Operations

Based on the analysis and summary in the introduction, the potential factors influencing the effectiveness of intermittent pumping wells were determined. These factors were categorized into three aspects based on their different sources of impact on intermittent pumping: reservoir and fluid parameters, production dynamic parameters, and artificial lift design parameters. It should be noted that different experts or application scenarios may use different classifications and designs, which could affect the results.

First, reservoir and fluid parameters reflect the physical properties and fluid characteristics of the oil reservoir itself, serving as the foundation for the production potential of oil wells. These parameters determine the well's production capacity, efficiency, and extraction methods. Second, production dynamic parameters reflect the actual performance of oil wells during the production process and are crucial for evaluating the well's production efficiency and adjusting production strategies. These parameters can be monitored in real-time or periodically to promptly identify production issues and take appropriate measures. Lastly, artificial lift design parameters involve human control and intervention in the well extraction process, aiming to optimize the operating efficiency of the pumping unit and the well's production capacity. These parameters need to be adjusted and optimized according to the actual conditions and extraction needs of the well.

For the aforementioned three aspects of factors, the analytic network process was applied to calculate the weights of each factor's indicators. The six core factors with higher weights were then identified as the considerations for establishing the intermittent pumping well selection method.

The analytic network process (ANP) was proposed by American operations researcher T. L. Saaty in 1996. It is an extension of his previously developed analytic hierarchy process (AHP) [21]. The ANP not only considers the hierarchical relationships between elements but also takes into account the interdependent relationships among them, making the decision-making process more comprehensive and precise.

The implementation process of the analytic network process (ANP) is typically refined into the following steps:

(1) Establishing the factor network structure model: Construct a network structure to deeply analyze the complex relationships between various factors, clarifying the intrinsic connections and dependencies among them. This step lays the foundation for subsequent quantitative analysis.
(2) Establishing the comparison judgment matrix: Use this as a quantitative tool for accurately measuring the relative importance of each factor. Building the judgment matrix not only requires a professional knowledge framework but also involves widely collecting expert opinions to ensure the comprehensiveness and accuracy of the evaluation. At the same time, it is necessary to conduct a logical consistency check on the judgment matrix to ensure its reasonableness and reliability, providing assurance for subsequent calculations.

(3) Calculation of factor index weights: Apply mathematical methods to process the judgment matrix, using rigorous mathematical calculations to determine the specific weight of each factor in the decision-making process.
(4) Comprehensive evaluation of factors: Based on the calculated weights and the network structure model, conduct a comprehensive evaluation to thoroughly analyze the significance of each factor.

2.1. Constructing the Network Structure Model for Influencing Factors

First, the interrelationships between the factors are obtained through expert surveys, and based on these relationships, a network structure model is established, as shown in Figure 1. The factor pointed to by the arrow is influenced by the factor at the tail of the arrow. A double-headed arrow indicates mutual influence between elements, and when elements within the same category influence each other, this is represented by a closed circular double-headed arrow.

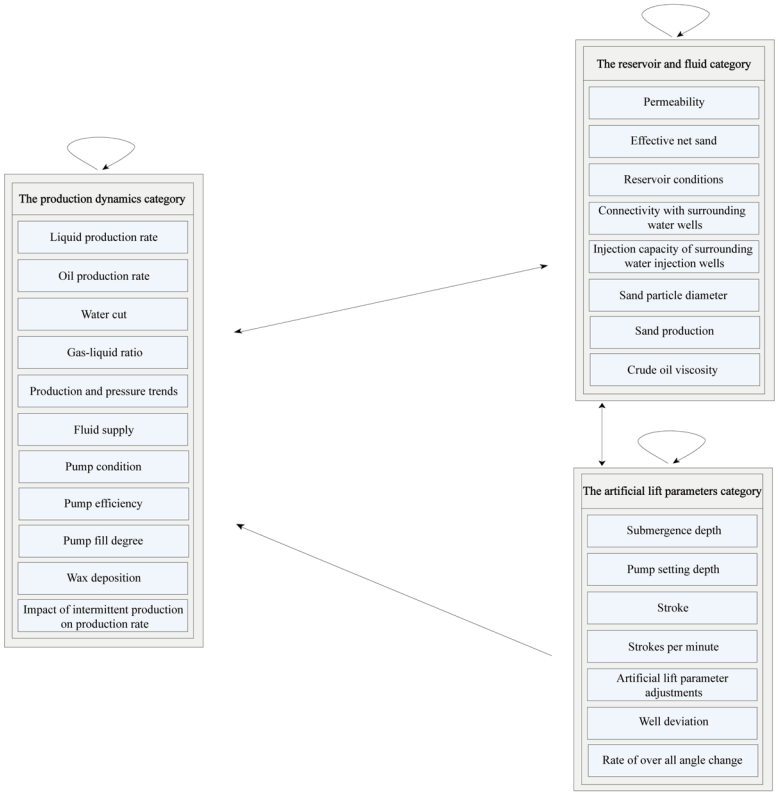

Figure 1. Network structure model diagram of various factors.

As shown in Figure 1, the reservoir and fluid category contains 8 factors, the production dynamics category contains 11 factors, and the artificial lift parameters category contains 7 factors.

2.2. Establishing the Judgment Matrix and Conducting a Consistency Check

To construct the judgment matrix, each factor with a subordinate relationship is used as a criterion, and the factors belonging to it are compared in pairs, assessing the degree of their importance [22]. The relative importance between pairs is typically quantified using the 1–9 scale method [23], as shown in Table 1.

Additionally, a consistency check must be performed on the judgment matrix. It typically follows these three steps [24]:

(1) Calculate the maximum eigenvalue of the judgment matrix, and use this maximum eigenvalue to compute the consistency index (CI) according to the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

where n is the order of the matrix, which means the number of factors, and λ_{max} is the maximum eigenvalue of the judgment matrix.

(2) Look up the corresponding random consistency index (*RI*) in Table 2.

(3) Calculate the consistency ratio (*CR*).

$$CR = \frac{CI}{RI} \quad (2)$$

If $CR \leq 0.1$, the consistency of the judgment matrix is considered acceptable. Otherwise, it is necessary to review and re-evaluate the judgment values in the matrix. If a factor is found to have a clear logical contradiction or inconsistency with other factors, reassess and adjust the value of that factor.

A comparison of the importance levels of certain factors is shown in Table 3.

Table 1. The 1–9 scale method for pairwise comparison.

Scale	Explanation
1	The two factors are equally important.
3	The former factor is slightly more important than the latter.
5	The former factor is significantly more important than the latter.
7	The former factor is extremely more important than the latter.
9	The former factor is strongly more important than the latter.
2, 4, 6, 8	The intermediate value between the adjacent judgments above.
Reciprocal of 1–9	The importance when the order of the two factors is reversed.

Table 2. Random consistency index (*RI*) for consistency check.

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.5200	0.8900	1.1200	1.2600	1.3600	1.4100	1.4600	1.4900	1.5200

Table 3. Scale of relative importance between factors in ANP analysis.

Judgment Criterion	Factor 1	Factor 2	Importance Level of Factor 1 Relative to Factor 2
Pump fill degree	Liquid production rate	Oil production rate	3
	Oil production rate	Production and pressure trends	5
	Liquid production rate	Pump efficiency	1
	Pump efficiency	Oil production rate	3

When taking the degree of pump filling as the judgment criterion, the liquid production rate and pump efficiency are equally important, while the pump efficiency is slightly more important than the oil production rate, and the liquid production rate is slightly more important than the oil production rate. The oil production rate is significantly more important than production and pressure trends. The scoring principles for other factors and the construction of the judgment matrix follow the same method as described above.

2.3. Indicator Weights of Influencing Factors

The calculated factor weights of influencing indicators are shown in Table 4. The local weight represents the weight of each factor within the categories of reservoir and fluid, production dynamics, and artificial lift design. The global weight is the final weight of each factor, considering the influence of the overall weights of the reservoir and fluid, production dynamics, and artificial lift design.

Table 4. Weight values of influencing factors in ANP analysis.

Factor Name	Local Weight	Global Weight
Permeability	0.2578	0.0386
Effective net sand	0.0007	0.0001
Reservoir conditions	0.0173	0.0026
Connectivity with surrounding water wells	0.0431	0.0065
Injection capacity of surrounding water injection wells	0.0427	0.0064
Sand particle diameter	0.3004	0.0450
Sand production	0.3113	0.0466
Crude oil viscosity	0.0269	0.0040
Liquid production rate	0.2878	0.1756
Oil production rate	0.0618	0.0377
Water cut	0.2597	0.1584
Gas–liquid ratio	0.0106	0.0064
Production and pressure trends	0.0242	0.0148
Fluid supply	0.0151	0.0092
Pump condition	0.0041	0.0025
Pump efficiency	0.1716	0.1047
Pump fill degree	0.0249	0.0152
Wax deposition	0.1221	0.0745
Impact of intermittent production on production rate	0.0182	0.0111
Submergence depth	0.8557	0.2055
Pump setting depth	0.0620	0.0149
Stroke	0.0115	0.0028
Strokes per minute	0.0067	0.0016
Artificial lift parameter adjustments	0.0641	0.0154
Well deviation	0.0000	0.0000
Rate of overall angle change	0.0000	0.0000

2.4. Comprehensive Evaluation and Screening of Influencing Factors

A comprehensive analysis of Table 4 reveals that factors such as the liquid production rate, oil production rate, pump efficiency, submergence depth, water cut, wax deposition, and sand production have received high weight values, highlighting their significant influence on the decision-making process. Considering that there are clear conversion formulas between the liquid production rate, oil production rate, and water cut, which indicate a strong correlation among the three, this study retained the liquid production rate and water cut as representative factors in the selection of intermittent pumping wells, while temporarily excluding the oil production rate to simplify the analysis and avoid data redundancy.

Based on this rationale and after careful screening, this study ultimately identified six core factors: liquid production rate, pump efficiency, submergence depth, water cut, wax deposition, and sand production, as the key considerations for intermittent well selection decisions. This selection not only simplifies the analytical framework but also ensures that the chosen factors comprehensively and accurately reflect the actual conditions of oil wells, providing robust data support for subsequent well selection decisions.

3. Research on Intermittent Pumping Well Selection Method Based on Fuzzy Logic

Fuzzy logic, as a mathematical tool for handling uncertainty and fuzziness, is commonly used in control systems, artificial intelligence, and other complex decision-making domains. For example, it has been applied in the optimization of cutting parameters in polymer material manufacturing and in the prediction of air bearing characteristics [25,26]. The Mamdani fuzzy inference system, as one of the reasoning methods within fuzzy logic, enables deductive computations from input to output through pre-established inference rules [27]. Its process generally encompasses the following key steps:

(1) Fuzzification: This step transforms crisp input values into fuzzy values within fuzzy sets. Fuzzification involves two parts: firstly, identifying the input and output vari-

ables, meaning the data to be fuzzified and the desired fuzzy output; secondly, selecting appropriate membership functions to map the input data onto fuzzy sets, representing their uncertainty or degree of vagueness.

(2) Inference Engine: Based on a predefined set of fuzzy rules and the membership information derived from fuzzified input variables, the inference engine employs logical reasoning to deduce fuzzy conclusions. Central to this process is the creation of a comprehensive and effective fuzzy rule base, reflecting the non-linear relationships and empirical knowledge about the system's variables. Subsequently, logical operations are applied to these rules and input memberships to generate fuzzy output sets, offering fuzzy guidance for decision-making.

(3) Defuzzification: After obtaining fuzzy conclusions, it becomes necessary to convert the fuzzy output sets into concrete, crisp numerical values. Defuzzification utilizes various methods, such as the center of gravity method or the maximum membership method, to map the fuzzy sets back to crisp values. This step ensures that the results of fuzzy reasoning can be practically applied, providing clear guidance for decision-making.

3.1. Fuzzification

Determining Input and Output Variables: Based on the findings in Section 2, a Mamdani-type fuzzy inference system is adopted to construct the intermittent well selection method. Pump efficiency, submergence depth, liquid production rate, water cut, wax deposition, and sand production are used as input variables, while the output variable is the intermittent operation decision.

Determining the membership function [28]: To precisely characterize the value features of the various influencing factors, this study adopted two typical types of membership functions when selecting the membership function: the trapezoidal function and the rectangular function.

Rectangular membership function:

$$\mu(x) = \begin{cases} 1 & x \le m \\ 0 & x \ge m \end{cases} \tag{3}$$

Trapezoidal membership function:

$$\mu_m(x) = \begin{cases} 0 & x \le m_1 \\ \frac{x-m_1}{m_2-m_1} & m_1 < x \le m_2 \\ 1 & m_2 < x \le m_3 \\ \frac{m_4-x}{m_4-m_3} & m_3 < x \le m_4 \\ 0 & x > m_4 \end{cases} \tag{4}$$

The selection rationale for each membership function is elaborated as follows:

(1) During the intermittent well selection process, for the four key factors of pump efficiency, submergence depth, liquid production rate, and water cut, when a factor's value exceeds a preset safe or optimal range, it does not necessarily mean that the well is unsuitable for intermittent pumping under the current conditions. The influence of these factors on intermittent pumping decisions exhibits fuzziness. These factors show some degree of uncertainty within specific intervals while displaying relatively clear states in other intervals. For example, regarding pump efficiency, when it is particularly low, intermittent pumping may be clearly needed; when pump efficiency is in the medium range, judgment needs to be made in combination with other factors; when pump efficiency is particularly high, intermittent pumping may clearly not be needed. Considering this characteristic, and to more accurately describe the fuzzy influence of these factors on intermittent well selection at different value levels, this study adopted trapezoidal membership functions. Trapezoidal functions effectively

reflect the smooth transition and clear delineation of membership degrees for these variables within certain intervals, thereby providing a more refined and scientific basis for rational intermittent well selection.

(2) In the decision-making process for intermittent well selection, wax deposition and the sand production rate, as two crucial factors, significantly impact well production performance and the lifespan of the well pumping system. For instance, regarding the sand production rate, when it exceeds certain limits, it can cause damage to the pump and other adverse effects, making the well unsuitable for intermittent pumping; when it is within certain limits, intermittent pumping may be clearly needed. Therefore, when considering their membership functions, this study adopted rectangular membership functions to precisely characterize the membership relationships of these two factors. With their clear boundary delimitations, rectangular membership functions can directly reflect whether the degree of wax deposition or the sand production rate has reached a certain critical threshold. This ensures decisive and accurate decision-making during intermittent well selection based on the definitive states of these factors.

The intermittent operation output variable clearly identifies whether a well is suitable for intermittent production. Using a binary label of "Yes" or "No", it directly reflects the selection result, concisely and intuitively conveying the decision information, as shown in Figure 2.

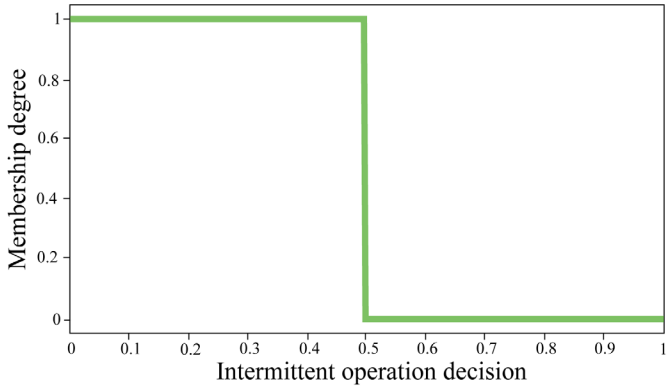

Figure 2. Membership function diagram of output factors.

3.2. Intermittent Well Selection Inference Method

In the fuzzy inference stage, a comprehensive system of association rules is established. These rules, when receiving input from influencing factors, utilize three clearly defined states: "None", "Meet", and "Not meet". "None" signifies instances where the current factor lacks a valid value due to missing data. "Meet" accurately indicates that the numerical value falls within the predefined range for that factor, representing a high degree of conformity. "Not Meet" denotes that the value fails to meet or exceeds the defined range, indicating a mismatch. For the output of the intermittent operation decision, two labels are employed: "Intermittent" and "Not intermittent". These labels directly and accurately convey the final judgment regarding the implementation of intermittent operation. A selection of fuzzy inference rules is presented in Table 4.

As shown in Table 5, this study established a rigorous decision-making logic to address data gaps and anomalies. Specifically, when the number of missing input data points for the four core factors—pump efficiency, submergence depth, water cut, and liquid production rate—is less than three, intermittent operation decisions can still be made based on the remaining valid data. However, if three or more of these key factors are missing input data, a conservative "Not Intermittent" decision is made to mitigate potential risks. For the two crucial influencing factors, sand production and wax deposition, a stricter criterion is adopted: if their input data fall outside the predefined acceptable range, an immediate

"Not Intermittent" decision is made, regardless of the values of other factors. This approach ensures the safety and specificity of the decision-making process in such scenarios.

Table 5. Partial fuzzy inference rule table for well selection.

Input						Output
Pump Efficiency	**Submergence Depth**	**Water Cut**	**Liquid Production Rate**	**Sand Production**	**Wax Deposition (Thickness)**	**Intermittent Operation Decision**
None	Meet	Meet	Meet	Meet	Meet	Intermittent
None	Meet	None	Meet	Meet	Meet	Intermittent
None	None	None	Meet	Meet	Meet	Not intermittent
Meet	Meet	Meet	Meet	Not meet	Meet	Not intermittent
Meet	Meet	Meet	Meet	Meet	Not meet	Not intermittent
Meet	Meet	Meet	Meet	Meet	Meet	Intermittent

3.3. Defuzzification

Considering that each factor in the intermittent well selection process holds a certain level of importance and contribution to the final decision, and to ensure the comprehensiveness, scientific validity, and accuracy of the decision-making, the centroid method, as an effective defuzzification technique, is introduced into this complex decision-making process. By calculating the centroid of each fuzzy output set, which represents the weighted average of all possible factor values and their corresponding membership degrees, the centroid method transforms the fuzzy reasoning results into a clear and concrete well selection decision. This decision comprehensively considers the importance and contribution of all influencing factors, reflecting the comprehensiveness and scientific rigor of the decision-making process. The calculation formula for the centroid method is as follows:

$$y' = \frac{\sum_{i=1}^{n} \mu_i(y_i) \cdot y_i}{\sum_{i=1}^{n} \mu_i(y_i)} \tag{5}$$

In the formula, y' represents the final output value; y_i represents the factor value in the fuzzy output set; $\mu_i(y_i)$ represents the membership degree of the i-th factor value; and n is the number of factor values in the fuzzy output set.

4. Application Example of the Intermittent Well Selection Method

To comprehensively validate the application effect of the intermittent well selection method in actual oilfield production, this study conducted intermittent well selection experiments in two different oilfield blocks, A and B, in China. During the experiment, representative wells' real production data were systematically collected, including key parameters such as liquid production rate, pump efficiency, and water cut. Additionally, data analysis and cleaning operations were performed to ensure data reliability [29]. Subsequently, based on the specific evaluation criteria for intermittent pumping wells in oilfield blocks A and B, this study characterized the input membership functions. Relying on the actual production data from each block, suitable wells for intermittent pumping were selected. The selection results were then compared with the judgments of professional oilfield engineers. Finally, intermittent pumping trials were conducted on the suitable wells, and the production data before and after the trials were compared and analyzed.

Furthermore, for oilfield applications and validations that have not yet been addressed in this study, it is necessary to redefine the input membership functions in accordance with the well selection criteria specific to each oilfield block. Subsequently, the well selection model should be adjusted to accommodate the particular requirements of the respective oilfield block.

4.1. Example of Input Membership Function for Intermittent Pumping Wells

Based on the actual well selection requirements of oilfield blocks A and B, the input membership functions for intermittent pumping well selection were characterized, as shown in Figure 3.

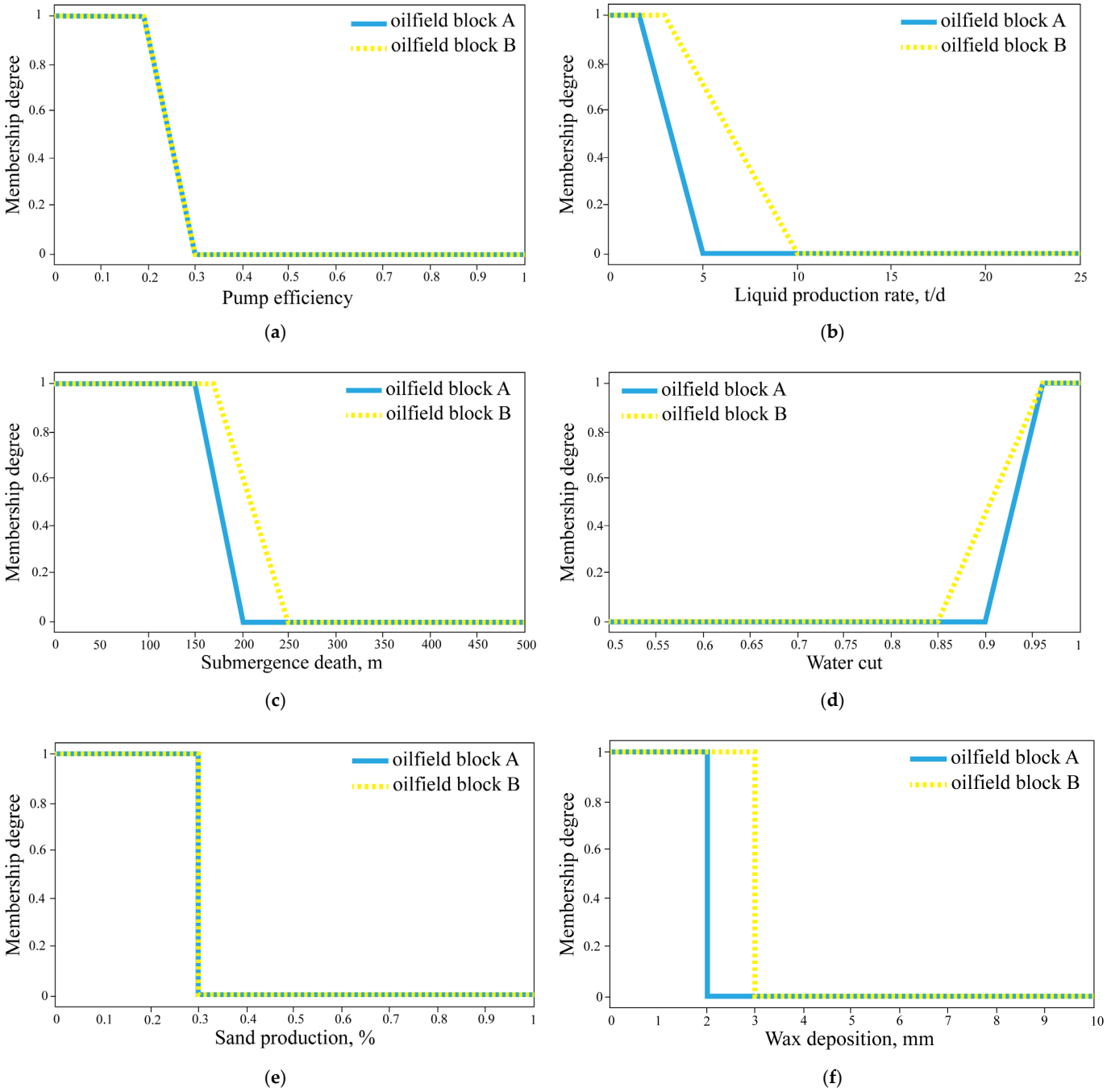

Figure 3. Membership function diagram of input factors for oilfield blocks A and B. The green line in the figure represents the overlapping section of the membership function selection for two oilfield blocks. (**a**) Pump efficiency. (**b**) Liquid production rate. (**c**) Submergence depth. (**d**) Water cut. (**e**) Sand production. (**f**) Wax deposition.

Table 6 presents the requirements for intermittent pumping well selection in oilfield block A.

Table 6. Well selection requirements for oilfield block A.

Oilfield Block A	Pump Efficiency	Submergence Depth, m	Water Cut	Liquid Production Rate, t/d	Sand Production, %	Wax Deposition, mm
Range of values	≤0.3000	≤200	≥0.9000	≤5	≤0.3000	≤3.0000

The intermittent pumping selection requirements for oilfield block B are shown in Table 7.

Table 7. Well selection requirements for oilfield block B.

Oilfield Block B	Pump Efficiency	Submergence Depth, m	Water Cut	Liquid Production Rate, t/d	Sand Production, %	Wax Deposition, mm
Range of values	≤0.3000	≤250	≥0.8500	≤10	≤0.3000	≤2.0000

4.2. Application and Analysis of Intermittent Pumping Well Selection Methods

Based on the actual production data of four oil wells obtained from oilfield block A and three oil wells from oilfield block B, we conducted intermittent pumping well evaluations in combination with the specific well selection requirements of each block. The assessment results are shown in Tables 8 and 9 Through comparative analysis, it was found that the judgment results were highly consistent with those of the oilfield professional engineers, but with significant time and labor savings. Subsequently, this study conducted intermittent pumping trials on the oil wells that were judged to be suitable for intermittent pumping, and the production data comparison results before and after the trials are shown in Tables 10 and 11.

Table 8. Example application of the intermittent pumping well selection method in oilfield block A.

Oilfield Block A	Pump Efficiency	Submergence Depth, m	Water Cut	Liquid Production Rate, t/d	Sand Production, %	Wax Deposition, mm	Intermittent Operation Decision
Oil well 1	0.2500	150	0.9200	4	0.3000	1.5000	Intermittent
Oil well 2	0.2000	210	0.9500	5	0.1000	2.0000	Intermittent
Oil well 3	0.2300	190	0.9300	6	0.2000	3.5000	Not Intermittent
Oil well 4	0.2500	130	0.9000	3	0.5000	1.0000	Not Intermittent

Table 9. Example application of the intermittent pumping well selection method in oilfield block B.

Oilfield Block B	Pump Efficiency	Submergence Depth, m	Water Cut	Liquid Production Rate, t/d	Sand Production, %	Wax Deposition, mm	Intermittent Operation Decision
Oil well 1	0.2000	220	None	8	0.2500	2.0000	Intermittent
Oil well 2	0.3500	180	0.9000	7	0.2000	1.5000	Intermittent
Oil well 3	0.2500	230	0.9300	10	0.3500	2.5000	Not Intermittent

Table 10. Comparison of production data before and after intermittent pumping in oilfield block A.

Oilfield Block A	Liquid Production Rate Before Intermittent Pumping, t/d	Liquid Production Rate After Intermittent Pumping, t/d	Daily Electricity Consumption Before Intermittent Pumping, kWh	Daily Electricity Consumption After Intermittent Pumping, kWh
Oil well 1	4	3.9000	114.9000	101.8000
Oil well 2	5	4.9500	103.7000	89.8000

Table 11. Comparison of production data before and after intermittent pumping in oilfield block B.

Oilfield Block B	Liquid Production Rate Before Intermittent Pumping, t/d	Liquid Production Rate After Intermittent Pumping, t/d	Daily Electricity Consumption Before Intermittent Pumping, kWh	Daily Electricity Consumption After Intermittent Pumping, kWh
Oil well 1	8	8.9000	214.9000	191.8000
Oil well 2	7	6.9500	193.7000	169.8000

The data obtained from four of the oil wells are shown in Table 8.

As shown in Table 8, for oilfield block A, all data for oil well 1 meet the well selection requirements for oilfield block A, as outlined in Table 6, so the judgment result is intermittent extraction. For oil well 2, except for the subsidence death, all other criteria meet the well selection requirements in Table 6. Upon comprehensive evaluation, this well was selected for intermittent extraction. For oil well 3, except for the wax deposition (thickness) exceeding the requirements, all other criteria meet the well selection requirements in Table 6. However, the wax thickness does not meet the intermittent extraction selection standard, so the judgment is no intermittent extraction. For oil well 4, except for the sand production not meeting the requirements, all other criteria also meet the well selection requirements in Table 6. However, the sand production also does not meet the intermittent extraction selection standard, so the judgment is also no intermittent extraction.

The data obtained from three of the oil wells are shown in Table 9.

As shown in Table 9, for oilfield block B, in oil well 1, except for the missing water cut data, all other criteria meet the well selection requirements for oilfield block B as outlined in Table 7, so the judgment is intermittent extraction. In oil well 2, the pump efficiency is 0.35, which does not meet the requirement, but all other criteria meet the well selection requirements in Table 7, so the judgment is intermittent extraction. In oil well 3, the sand production and wax deposition do not meet the standards, although other data meet the well selection requirements in Table 7, the comprehensive judgment is no intermittent extraction.

Intermittent pumping tests were conducted on the two oil wells in Table 8 that were determined to be suitable for intermittent pumping. The comparison of production data before and after the tests is shown in Table 10.

As shown in Table 10, after the intermittent pumping operation, the fluid production of well 1 decreased by 2.5%; however, the electricity consumption decreased by 11.4% compared to before intermittent pumping. Meanwhile, the fluid production of well 2 decreased by 1%, and the electricity consumption decreased by 13.4% compared to before intermittent pumping. From this, it can be judged that the wells undergoing intermittent pumping have a relatively small decrease in fluid production, but there is a significant reduction in electricity consumption, which greatly increases the efficiency of the oil wells.

Intermittent pumping tests were conducted on the two oil wells in Table 10 that were determined to be suitable for intermittent pumping. The comparison of production data before and after the tests is shown in Table 11.

As shown in Table 11, after implementing intermittent pumping operations, oil well 1 experienced an 11.3% increase in liquid production rate, while its electricity consumption decreased by 10.7% compared to before the intermittent pumping. For well 2, the liquid production rate decreased by 0.7%, and electricity consumption dropped by 12.3% compared to before the intermittent pumping. This indicates that for oilfield block B, after executing intermittent pumping on well 1, liquid production increased while electricity consumption declined. In the case of well 2, intermittent pumping resulted in a slight decrease in liquid production but a significant reduction in electricity consumption. Overall, performing intermittent pumping operations on wells identified for such interventions led to improved well efficiency.

Regarding the intermittent pumping tests conducted on the oil wells in the above two oilfield blocks that were clearly identified as needing intermittent pumping, the test results show that after undergoing intermittent pumping operations, these wells not only achieved significant reductions in production costs but also greatly shortened the production cycle, while the overall output remained basically stable. This outcome strongly confirms the necessity of implementing intermittent pumping for these wells. The successful implementation of the intermittent pumping tests not only demonstrates the high effectiveness of this method in selecting wells for intermittent pumping but also reflects its convenience and practicality in actual operations, providing strong support for the optimization and enhancement of oilfield production management. In current field applications, no anomalies or unexpected outcomes have been detected. Nevertheless, should such circumstances emerge in future implementations, the intermittent pumping well selection model can be refined through modifications to membership functions, replacement of existing functions, and the incorporation of additional influencing factors, thereby improving the model's adaptive capabilities.

5. Discussion

As the complexity of oilfield management continues to increase, traditional well selection methods have become increasingly inadequate for modern management needs. This paper proposes an intermittent pumping well selection method based on the analytic network process (ANP) and fuzzy logic, providing oilfield managers with a new and more flexible decision support tool.

Firstly, as oil well production efficiency is influenced by multiple complex and interrelated factors, the ANP is employed to examine these numerous factors. By analyzing the intrinsic relationships among various factors, the system evaluates and calculates the weight of each factor, thereby identifying the six most representative and influential key factors. The application of the ANP not only simplifies the complex well selection process but also ensures comprehensive coverage and consideration of key influencing factors, providing reliable data support and a theoretical foundation for subsequent intermittent pumping well selection.

Secondly, based on the selected key influencing factors, the intermittent pumping well selection model established using the fuzzy logic system transforms the fuzzy and uncertain relationships among various factors into a clear decision-making basis through the precise definition of fuzzy sets and the construction of fuzzy rules. The introduction of fuzzy logic enables the decision model to better handle complex and variable production conditions, thereby accurately determining which wells are suitable for intermittent pumping under the current production conditions. This method improves the accuracy, reliability, flexibility, and adaptability of the model, allowing it to meet the specific needs and complex environments of different oilfield blocks.

Finally, the effectiveness and reliability of this method were demonstrated through field application experimental results. The method was applied to two different oilfield blocks, and well selection experiments were conducted based on actual data, as well as intermittent pumping tests on the selected wells. The experimental results show that the selected wells achieved significant production efficiency improvements after implementing intermittent pumping, proving the scientific nature, effectiveness, reliability, and stability of the method in practical applications. Furthermore, by flexibly adjusting the range and weight of factors in the model, the method demonstrates good adaptability and scalability.

Consequently, the proposed methodology not only introduces innovative technical approaches for the selection of intermittent production wells but also equips oilfield managers with a more versatile and adaptive decision-support tool. This enables the nuanced adjustment of production strategies in accordance with the prevailing circumstances, thereby facilitating the optimal allocation of oilfield resources and fostering sustainable development. Nonetheless, as oilfield development progresses, the operational milieu is poised to

become increasingly intricate and heterogeneous, imposing more rigorous exigencies on well selection methodologies [30].

In light of this, the present research delineates two prospective avenues for the expansion of this methodological inquiry: One direction involves the incorporation of additional influential factors, including geological conditions and reservoir characteristics, to augment both the precision and inclusivity of well selection. Furthermore, exploratory endeavors may be directed towards the amalgamation of this method with other cutting-edge technologies, such as artificial intelligence and big data analytics, thereby enhancing its decision-making efficacy and cognitive sophistication. Moreover, while the field application validation presented in this study has yielded substantial outcomes, the sample size and breadth necessitate expansion. In future endeavors, the compilation of a more extensive dataset comprising field data from diverse oilfields could facilitate a more thorough verification and optimization of the method, thereby ensuring its robustness and dependability across disparate oilfield blocks and complex environmental settings.

6. Conclusions

An innovative approach combining analytic network process (ANP) and fuzzy logic is proposed in this paper for intermittent pumping well selection, with the objective of optimizing and improving the precision of the well selection process. First, through ANP, numerous complex and interrelated influencing factors were thoroughly analyzed, leading to the identification of six high-weight and highly representative key factors. This process simplified the well selection procedure while ensuring a comprehensive coverage and consideration of critical influencing factors. Subsequently, a fuzzy logic model based on these factors was constructed, transforming fuzzy and uncertain relationships into clear decision-making criteria, thus achieving efficient extraction of key information from complex factors and enhancing the flexibility and adaptability of the decision-making process. Finally, through field application validation, all selected wells demonstrated significant production efficiency improvements after implementing intermittent pumping, proving the method's effectiveness and reliability while showing its good adaptability and scalability.

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