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A Novel Model for the Real-Time Evaluation of Hole-Cleaning Conditions with Case Studies

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Abstract: The main challenge in deviated and horizontal well drilling is hole cleaning, which involves the removal of drill cuttings and maintaining a clean borehole. Insufficient hole cleaning can lead to issues such as stuck pipe incidents, lost circulation, slow rate of penetration (*ROP*), difficult tripping operations, poor cementing, and formation damage. Insufficient advancements in real-time drilling evaluation for complex wells can also lead to drilling troubles and an increase in drilling costs. Therefore, this study aimed to develop a model for the hole-cleaning index (*HCI*) that could be integrated into drilling operations to provide an automated and real-time evaluation of deviated- and horizontal-drilling hole cleaning based on hydraulic and mechanical drilling parameters and drilling fluid rheological properties. This *HCI* model was validated and tested in the field in 3 wells, as it was applied when drilling 12.25″ intermediate directional sections and an 8.5″ liner directional section. The integration of the *HCI* in Well-A and Well-B helped achieve much better well drilling performance (50% *ROP* enhancement) and mitigate potential problems such as pipe sticking due to hole cleaning and the slower rate of penetration. Moreover, the *HCI* model was also able to identify hole-cleaning efficiency during a stuck pipe issue in Well-C, which highlights its potential usage as a real-time model for optimizing drilling performance and demonstrates its versatility.

Keywords: real time evaluation; deviated wells; hole-cleaning index (*HCI*); case studies; drilling performance improvement

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1. Introduction

Drilling vertical and more directional wells for the oil and gas industry is necessary to meet demand for global resources [1]. Drilling troubles are a constant, and most of these drilling problems are stuck pipe incidents due to improper hole cleaning, lost circulation, and well control incidents [2,3]. Optimization of downhole cleaning during drilling can be achieved either by improving engineering aspects or by enhancing drilling fluid properties using suitable chemical additives, and most of the time, both are applied appropriately [3]. In planning and designing the drilling of wells, drilling time and flat time must be suitably optimized to obtain the best drilling efficiency and cost effectiveness [4,5]. Hole cleaning during drilling plays a significant role in reducing drilling time by ensuring an enhanced rate of penetration (*ROP*) and a flat time by minimizing tripping operations, pumping of sweep pills, time of circulation, and time spent running casing, while improving cementation integrity and efficiency [6]. Improper hole cleaning causes drilling problems such as high or erratic trends of equivalent circulating density, torque and drilling drag, wellbore instability, high annulus pressure, lost circulation, tight hole sections encountered during tripping, and stuck pipe and well control incidents [7]. Hole cleaning is an effective tool used to overcome wellbore instability during drilling in case cutting accumulation and shale sloughing and caving are encountered. Cutting accumulation and shale caving will lead to difficult tripping operations resulting from pipe sticking [8]. In fact, approximately

33% of stuck pipe incidents in deviated and horizontal directions are caused by inadequate downhole cleaning while drilling, making it a significant contributor to these types of events [4,9,10]. Moreover, effective hole cleaning is a crucial aspect of maximizing production rates in a well, as it can significantly impact the success of subsequent techniques such as acidizing and CO_2 injection. By ensuring that the wellbore is adequately cleaned during drilling, the efficiency of these methods can be improved, reducing the risk of problems such as stuck pipe, borehole instability, and reduced production rates [11–14]. More importantly, the upwards flow velocity exceeding the speed of solids settling in the drilling fluid is the main condition of cutting removal while drilling vertical wells [7]. In the case of deviated and horizontal drilling, it is more difficult to fulfil this condition [8]. As the angle of the borehole increases, the direction of settling of fractured rock particles from the borehole axis changes. As a result, cuttings begin to accumulate on the bottom wall of the borehole. The efficiency of clearing the cutting particles from deviated and horizontal drilling wells depends on the basic hydrodynamic indicators and technological parameters of the drilling regime, as in the case of vertical wells, and on the geometry of the annular space and borehole profile [2,3,15]. The borehole profile is determined by the zenith angle, and the geometry of the annulus is determined by the eccentric position of the drill string [16–18]. There are 3 zenith angle intervals that affect the degree of cleaning of the drilled cuttings: 0–10°, 10–30°, and 30–60° [3,19]. At small zenith angles (0–10°), the particles settle in the direction of the bottom hole due to gravity acting on them. At medium values of the zenith angle (10–30°), the density and viscosity of the cuttings increase, which leads to possible accumulation of sludge at the bottom-hole bottom. If the zenith angle reaches 30–60°, the friction forces increase, and the particle sliding speed slows down, possibly even to a complete stop [20–22]. The efficiency of cutting removal also depends on the flow velocity profile in the annulus. In the concentric annulus of a vertical well, the drilling fluid velocity and energy are uniformly distributed relative to the drill string. As a result, the drill string is arranged eccentrically in the borehole. Therefore, there is a shift in the velocity profile. The consequence of this is that the flow velocity above the drill string is maximum and the velocity on the left and right sides of the drill string space is minimum. Sludge build-up occurs, and "stagnation zones or dead zones" are formed [3,19]. Another factor affecting bottom-hole cleaning is the velocity of the drilling fluid in the annulus. In laminar drilling-fluid mode, good cleaning of broken rock occurs when the rheological properties of the drilling fluid are properly selected. In turbulent mode, most of the solids are carried out of the borehole by the flow. The rheology of the drilling fluid has much less influence. However, the turbulent flow mode can be used only at a given flow rate of drilling pumps, low erosion of borehole walls, and high velocity of drilling fluid movement in the borehole space [23]. Another factor that influences bottom-hole cleaning is the rheological properties of the drilling fluid. It is possible to control the rheological properties of drilling fluids by treatment with special chemical additives [24]. Thus, the regulation of wellbore drilling performance is one of the main objectives of well drilling. All rheological characteristics of drilling fluids and hydrodynamic characteristics should be taken into account in a hydraulic well-drilling program [25–27]. Correctly selected formulation and rheological properties of the solution along with optimal technological parameters of the drilling process will allow high productivity and quality of drilling work to be achieved. Moreover, effective hole cleaning is a crucial aspect of maximizing production rates in a well, as it can significantly impact the success of subsequent techniques such as acidizing and CO_2 injection. By ensuring that the wellbore is adequately cleaned during drilling, the efficiency of these methods can be improved, reducing the risk of problems such as stuck pipe, borehole instability, and reduced production rates [11–14]. In addition, enhancing the effect of these parameters can assist in maintaining the carrying capacity of drilling fluids, which in turn can lead to an improvement in the design of wellbores [24]. Numerous studies have been conducted to investigate the parameters that affect hole-cleaning effectiveness. Raed et al. showed that drill pipe rotation is crucial for cutting removal in laminar and transition flow [23]. Meanwhile, multiple researchers have investigated cutting transport over the past few decades and created a variety of mechanistic and semimechanistic models to explain flow features [25–27]. Mohammadsalehi et al. developed an extensive approach that utilized Larsen's model and Moore's correlation for estimating and identifying the minimum flow rate that is needed for cutting removal across all inclination angles, which range from 0° to 90°. This was done to determine and estimate the bare minimum flow rate necessary for cutting removal at each and every inclination angle [28]. Recently, in a real-time evaluation, Al Rubaii et al. proved that optimizing the usage of the carrying-capacity index (*CCI*) and the concentration of cuttings in the annulus (*CA*) can considerably improve hole-cleaning effectiveness and boost *ROP*. These two variables are collectively referred to as the "concentration of cuttings in the annulus." The model offers drilling engineers and drilling supervisors an efficient technique for determining the appropriate mud characteristics for effective hole cleaning, as well as the maximum *ROP* that can be achieved based on the volume of cuttings in the annulus [24]. Nonetheless, with regard to the cleaning of boreholes during drilling procedures, there appears to be a notable deficiency in some models regarding evaluating the drilling process in real time. Furthermore, these models are based on a limited number of parameters affecting the status of hole cleaning. Therefore, the main objective of this study is to introduce a newly developed hole-cleaning index (*HCI*) based on Robinson's model that was developed in 2004 [29] to achieve effective downhole cleaning by applying the required adjustment to optimize the drilling process. This method implements automated carrying-capacity indicator modifications. The developed *HCI* enables real-time monitoring and evaluation of the status of hole cleaning during drilling. The study extensively explains the status of hole-cleaning models, as demonstrated in Figure 1. The paper delineates diverse real-time models that function as indicators for assessing hole cleaning. Furthermore, the mathematical formulation of the novel *HCI* model is expounded, encompassing all pertinent variables essential for the real-time assessment of hole-cleaning conditions. The significance of the *HCI* model as a novel index model is underscored by its validation through field applications.

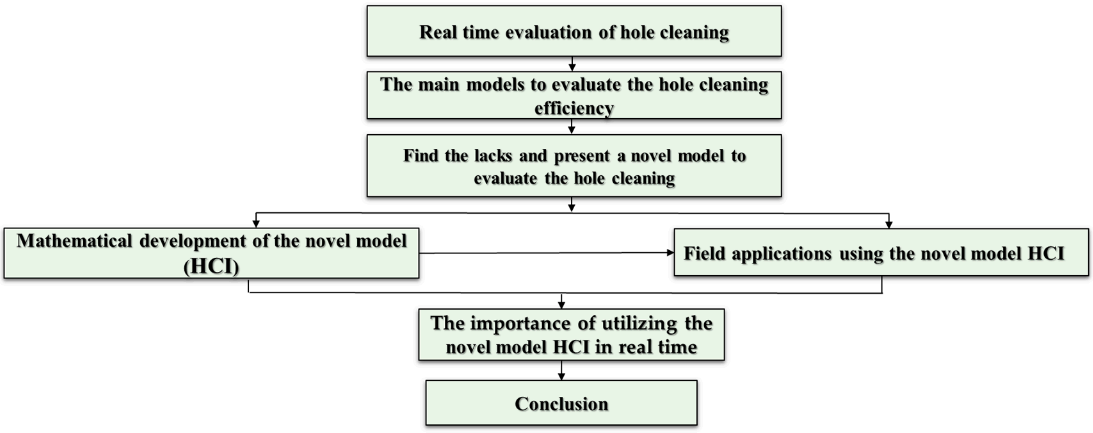

Figure 1. The flowchart outlining the various topics discussed and the systematic order in which they are presented.

2. Status of Hole-Cleaning Models

Hole cleaning is a fundamental function of mud, and this function is also the most used and misunderstood. Cleaning of deviated holes is most challenging because of changing formation lithologies and the drill cuttings. In addition, when the cutting beds (cutting accumulation height) are at a hole inclination of 35–50 degrees, the drill cuttings are more likely to slide downwards, negatively affecting hole cleaning [30–32].

Even though increasing the mud flow rate can reduce the height of the bed of drill cuttings, it will not be very effective in directional wells [30,33,34]. Pigott (1935) recommended that the concentration of the cuttings in the annulus must remain less than 5% to prevent stuck pipe problems [35,36]. Newitt et al. (1961) found a precise equation for drilling cuttings volumetric concentration in the annulus for steady-state lifting of drill cuttings in a vertical tube [37]. Mitchell (1992) developed an equation for quantifying average cutting concentration in the annulus while drilling and after stopping circulation while making a connection [38]. Moreover, experimental investigations performed by Hussaini and Azar (1983) [39] and Azar (1990) [40] indicate that mud rheology also affects hole cleaning. The results of these investigations confirmed that the carrying efficiency of drilling mud increases when the percentage of the ratio between the mud yield point (*YP*) and the mud plastic viscosity (*PV*) is maximized. Larsen (1997) introduced a novel design model that facilitates the selection of appropriate hydraulic parameters by drilling engineers, thereby ensuring seamless drilling operations in high-angle boreholes ranging from 55° to 90° from the vertical. Empirical correlations were derived through a comprehensive experimental investigation of cutting transport in a flowloop with a full-scale diameter of 5 inches [41]. Moreover, Thonhauser (1999) introduced a mechanical device that was built to measure the amount of cuttings produced from the wellbore and analyze the hole-cleaning behavior. It was designed to provide the basis for real-time interpretation to optimize the circulating strategy and schedule, and to correlate the measured cutting flux with wellbore stability problems and overall drilling performance [42].

Furthermore, determining the density and size of drill cuttings during drilling to estimate the slipping velocity of drill cuttings is critical and vital. Additionally, when the viscosity of drilling mud is high, the effectiveness of mud in cleaning the hole by removing the drilled cuttings will also be high. Pipe rotation significantly improves the efficiency of hole cleaning if the drill string has a high eccentricity for both vertical wells [43] and inclined hole sections, according to Sanchez et al. [44].

Ogunrinde and Dosunmu (2012) developed a model to estimate the optimum *ROP* and *Q* to be used during drilling to maintain proper hole cleaning [15]. Samuel (2013) developed a modified model to predict drilling-string vibration during drilling to prevent damage or twisting-off of the *BHA* and associated poor hole cleaning [45].

Al-Azani et al. (2019) predicted real-time cutting concentration in the annulus by using *ANNs*, including back-propagation neural networks (BPNNs), radial basis functional networks (RBFNs), and *SVMs,* which are classified as artificial intelligence tools. The selected parameters were mud weight (*MW*), *PV*, *YP* temperature, mud pump flow rate (*Q*), *rpm*, *ROP*, pipe eccentricity, and inclination of the hole section. The results were validated with 116 experimental studies in the literature review domain. The accuracy was 0.9 R, and average absolute error (AAE) was less than 5% [1]. Al-Rubaii et al. (2020) developed a new real-time model for cutting concentrations in annuli based on the influence of *Q* and *ROP*, and the model was applied to real-time data and validated with Newtis and API models [46].

The model showed acceptable accuracy and results.

Al-Rubaii et al. (2018 and 2020) developed a new methodology for hole cleaning by improving *ROP* through evaluation and adjustment of the carrying-capacity index and accumulation of drill cuttings in the annulus of the drilled hole section simultaneously to improve drilling performance by more than 20% [24,46].

In addition, they modified the cutting carrying index by including cutting rise velocity with annular velocity and then applied the *CCI* to real-time data to monitor and evaluate the hole-cleaning efficiency and thereby optimize well and rig performance. Alawami et al. (2020) applied the hole-cleaning carrying-capacity index to real-time data to monitor and evaluate the hole-cleaning performance of drilled wells by using offline real-time data [10]. Mahmoud et al. (2020) modified the *CCI* to make it applicable in cleaning deviated hole sections. They modified the original carrying-capacity index by considering the effect of inclination on the annular velocity and equivalent circulating density [47]. Saihati et al. (2021) developed a predictive drilling torque model using machine learning techniques to monitor downhole conditions, such as poor hole-cleaning conditions [48]. Huaizhong et al. (2019) performed an experimental and numerical simulation study for cutting transport in a narrow annulus to maximize the rate of penetration of coiled tubing, which is partially underbalanced to solve the problem of wellbore instability. The outcomes of measurements were particle velocity, particle distribution, the phenomenon of collision of particles, and sinking and rising of particles. The obtained results were that the particle velocity declines with the increase in rotational speed and increases with the increase in flow rate [49].

Ytrehus et al. (2019 and 2021) used micronized barite to provide a lower-viscosity drilling fluid and nonlaminar flow, which is advantageous for particle transport in near-horizontal sections. They found that low-viscosity fluids are more efficient than viscous fluids at higher flow rates and low drill-string rotation. Different fields have applied oil-based drilling fluids with similar weights and varying viscosities, and positive results have been shown for cutting transport performance, hole-cleaning abilities, and hydraulic frictional pressure drop [50,51].

Pedrosa et al. (2022) investigated the influence of the rheological properties of three different types of fluids on the erodibility of the cutting bed. Three outcomes were measured: erodibility of the cutting bed, shear rates of different types of fluids, and flow rate dependency along the dune extent. The results showed that the cutting bed is eroded by dune movement [52].

Shirangi et al. (2022) developed a new digital-twin methodology for predicting drilling fluid properties to perform real-time calculations for hole cleaning by combining several models, using the large amount of offset data integrated in the model [53].

Elmgerbi et al. (2022) used two interconnected models to optimize drilling hydraulics. They used predictive and analytical models to predict, compute, and optimize surface drilling parameters [54].

Rathgeber (2023) examined the impact of pipe eccentricity, drill pipe rotation rates, pipe-to-hole area ratio, and wellbore flow area on cutting transport efficiency. The author additionally examined the influence of the ratio between the area of the pipe and the hole, as well as the area of flow within the wellbore, on the rotation of the drill pipe and the occurrence of flow channeling [55]. Moreover, Tables 1 and 2 show a summary of major findings for other studies related to hole-cleaning chemistry and engineering.

Table 1. Major findings in the field of hole-cleaning chemistry.

Year	Author	Technique	Output	Ref.
1906	Einstein	Rheology	Effective viscosity by including the influence of the concentration of solid particles	[56]
1992	Frenkel et al.	Wellbore instability	Kaolinite is the most dispersive, followed by illite, while smectite is not highly dispersive	[57]
1997	Zhou, Z.	Clay-swelling mechanisms	The expansion of clay is due to the increase in spacing between the clay layers	[58]
1998	McCollum	Rheology	Low mud rheology, reduction in the accumulation of cuttings and controlling solids in mud	[59]
2009	Stephens et al.	Swelling tests	High swelling percentage is a clear indicator of low efficiency of drilling fluid inhibition against swelling	[60]
2010	Zoback	Wellbore instability	Swelling of shale is due to the increase in vapor pressure within shale, leading to weakening of adherence and development of washout	[61]
2010	Abedian and Kachanov	Rheology	Effective viscosity of a Newtonian fluid with rigid spherical particles	[62]
2016	Aberoumand et al.	Rheology	Nano-fluid OBM viscosity	[63]
2018	Deng	Rheology	Higher bentonite concentration and a lower biopolymer concentration normally showed better hole-cleaning capacity	[64]
2019	Vanessa Boyou et al.	Rheology	Nanosilica WBM improves the transport efficiency of cuttings	[65]
2020	Ofei et al.	Rheology	By increasing mud density, hole-cleaning efficiency can be increased	[66]
2020	Sargani et al.	Rheology	*CCI* showed a high value at a 60/40 oil–water ratio	[7]
2020	Alsaba et al.	Rheology	MgO showed the highest improvement in hole cleaning, while TiO_2 resulted in the lowest improvement	[67]

Table 1. *Cont.*

Year	Author	Technique	Output	Ref.
2021	Abbas	Rheology	Cellulose nanoparticles as a perfect substitute for oil-based muds, improving the transport efficiency of cuttings	[68]
2022	Mohamed et al.	Rheology	Shape-memory polymer increases viscosity at low shear rates for better hole cleaning	[69]
2023	Xie et al.	Rheology	Novel nanocomposite-based thermo-associating polymer/silica nanocomposite enhanced the overall hole cleaning	[70]

Table 2. Major findings in the field of engineering.

Year	Author	Technique	Output	Ref.
1985	O'brien	Factors	A higher yield point value is required with larger cuttings	[71]
1991	Becker And Azar	Factors	Impact of inclinations on cutting bed and cutting concentration	[32]
1992	Luo et al.	Rheology and Factors	The rheology factor and the corrected minimum required flow rate with the used *ROP* and induced washout during drilling	[72]
1994	Marco Rasi	Indicators	Cutting bed height and hole-cleaning ratio (HCR)	[73]
1995	Beck	Rheology	Qualitative relationships between the rate of penetration and the rheological properties of the drilling fluid (*PV*, flow behavior index (n), Reynold number)	[74]
2000	Adari et al.	Factors	Ranked the hole-cleaning factors in drilling and the time to effectively clean the wellbore	[75]
2006	Berg et al.	Modelling	Flowchart for ensuring effective displacements for wellbore cleanness of open hole and cased hole prior to running completion	[76]
2007	Shariff et al.	Factors	Eccentricity and cutting concentration	[77]
2009	Saasen et al.	Factors	Drill-string rotation in a deviated hole with an appropriate flow rate can remove the bed of cuttings, and an optimal hole cleaning can be achieved	[50]
2011	Malekzadeh and Salehi	Modelling	The optimum flow rate ensuring both good hole cleaning and drilling hydraulics in a directional well to achieve an optimized *ROP*	[78]
2019	Alkinani & Al-Hameedi.	Rheology	ECD increases with *PV* and solid content, while it decreases slightly or is mostly stable with increasing values of *YP*	[79]
2021	Ahmed, A et al.	Modelling	The important parameter for hole cleaning with an engineering methodology to consider is the hole enlargement	[80]
2022	Jimmy et al.	Modelling	A new cutting lifting factor	[81]
2023	Iqbal et al.	Rheology	Raising viscosity enhances cutting transport performance but decreases performance in transition and laminar	[82]

Several models and studies have been discussed in the preceding text. Notably, Ogunrinde and Dosunmu developed a model to estimate the optimal *ROP* and flow rate, which demonstrated high accuracy in real-time drilling operations [45]. Similarly, Saihati et al. proposed a predictive drilling torque model [48], while Elmgerbi et al. utilised two interconnected models to optimise drilling hydraulics. Specifically, they employed predictive and analytical models to predict, compute, and optimise surface drilling parameters [54]. These models have shown promising results in enhancing drilling efficiency and accuracy. Notwithstanding the plethora of models and studies available, the *CCI* model, as proposed by Robinson [29], exclusively takes into account the adequacy of vertical transportation of cuttings, without providing any insight into the actual quantity of cuttings present, and is restricted to application within the drill pipe. Consequently, it is imperative to devise an innovative model that takes into account all the significant variables that impact the state of hole cleaning. Additionally, the proposed approach should be authenticated by utilising real-time field data and historical data from previously drilled wells. The following two sections delineate the mathematical development of the novel *HCI* and its implementation and verifications in three wells.

3. Development of a Novel Hole-Cleaning Index

The novel real-time automated model of the status of hole cleaning developed in this study is based on the carrying-capacity index of cuttings developed by Robinson in 2004 [29]. Ideally, Robinson created a model that utilizes the power law constant, mud weight, and annular velocity to estimate the changes in pressure differential at the bottom of a hole based on the mud weight and cuttings in the annulus. The calculation procedure assumes that annular pressure losses from drilling fluid flow remain constant, and the accuracy of current calculations is not considered precise enough to include them in this process. Therefore, the carrying capacity of the drilling fluid can be estimated using the carrying-capacity index (*CCI*), shown in Equation (1) [29].

$$CCI = \frac{k \times AV \times MW}{400,000} \quad (1)$$

where k is the consistency index, which can be obtained from Equation (2) based on [83–85], AV is the average annular velocity (ft/min), and MW is the drilling fluid density (pcf).

$$k = ((PV + YP))(510)^{1-n} \quad (2)$$

where n is the flow behavior index, PV is the plastic vicosity (cP), and YP is the yield point (lb/100 ft^2).

More importantly, based on the Robinson results, when the borehole is effectively cleaned, the drilling rate initially decreases until the first drilled solids reach the surface. However, as these solids are removed, the bottom-hole pressure still increases, albeit at a slower rate. As more solids are eliminated due to good carrying capacity, the bottom-hole pressure starts to decrease. The first solids typically reach the surface when the bit reaches a depth of 11,100 ft. The *ROP* then decreases more gradually until the bit reaches a depth of 11,200 ft. At this point, enough drilled solids are being removed that the drilling rate actually increases, as illustrated in Figure 2a. In contrast, if the hole cleaning is poor, drilled solids continue to accumulate in the annulus, and the drilling rate does not show significant abrupt changes. This effect is demonstrated in terms of the pressure differential during drilling, as shown in Figure 2b [29].

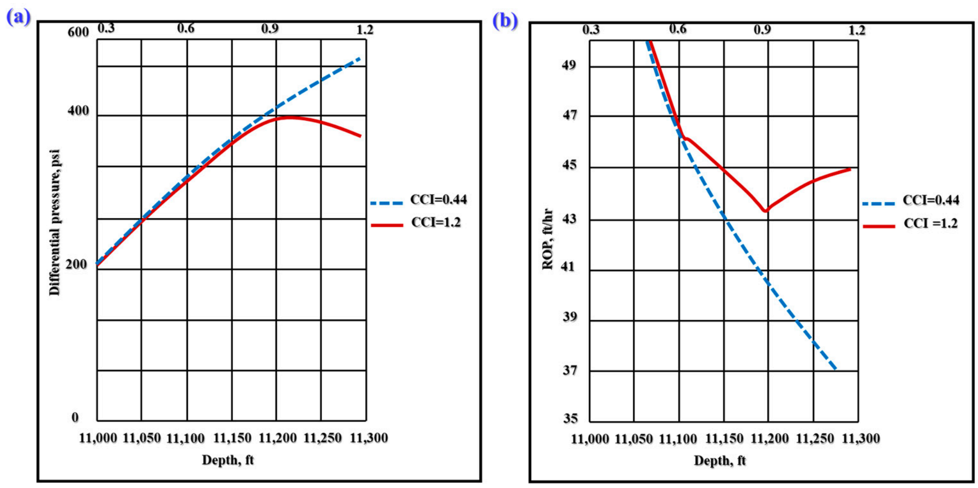

Figure 2. The *CCI* effect on differential pressure (**a**) and *ROP* (**b**) based on [29].

Although the sharpness and tumbling movement of the cuttings in the annulus can be used by the *CCI* to determine whether they are being carried properly in a vertical well, it does not reveal how many cuttings are actually present and is only applicable inside the drill pipe, in accordance with [29,86]. Moreover, additional parameters, such as hydraulic velocities, must be taken into account to achieve a more accurate evaluation of hole-cleaning performance in deviated and horizontal drilling. The drilling fluid's rheological characteristics, which include the low-shear yield point (*LSYP*) parameter, are a significant factor [2]. The calculated cutting slip and annular velocities must also be taken into account. Cutting slip is the difference between the velocities of the drilling fluid and the cuttings, whereas annular velocity is the velocity of the drilling fluid within the annulus that exists between the drill string and the wellbore. These parameters can be used to calculate the amount of cuttings that are transported to the surface and how well holes are cleaned [53]. Therefore, the novel index indicator considers all the important factors affecting the status of hole cleaning and is called the hole-cleaning index (*HCI*). It was developed starting from the *CCI* calculated using Equation (1) [29]. Moreover, Appendix A shows a flowchart for the development of the *HCI* starting from *CCI*.

More importantly, in Equation (2), *PV* represents the mechanical friction between the drilling fluid solids and drilling fluid that causes resistance to flow [87]. *YP* is the minimum value of stress that is required to move the fluid [48]. R_3 is the viscometer reading at 3 rpm, and R_6 is the viscometer reading at 6 rpm, which can be used to predict the yield point at a low shear rate that can be defined as *LSYP*. Specifically, *LSYP* can contribute significantly to hole-cleaning efficiency and the ability to transport drill cuttings in the drilling of directional wells, and it is as critical and important as *YP* during well drilling. In drilling operations practices, it is highly recommended to have increased *YP* and a decreased *LSYP* [88]. In addition, Bern et al. defined *LSYP* as the minimum yield stress for preventing solids settling (sagging) [89]. The value of *LSYP* can be dramatically decreased by increasing the pH because the increase in pH readings can support the minimization of the bentonite's dispersion particles, and then, the particles of bentonite will not assist the fluid viscosity being established. Hence, the lifting capacity of drilling mud to transport the generated drill cuttings will be minimized [90]. The standard API of measuring the low-shear yield point is defined as ($LSYP = 2R_3 - R_6$), which is used to estimate the proper yield stress [91]. For a newly developed *HCI*, the *LSYP* was considered for better simulation of hole conditions and rheological drilling fluid influences during drilling operations. Therefore, *PV* and *YP* can be modified based on the *LSYP*, as shown in Equations (3) and (4), based on [2].

$$PV = R600 - R300 = PV_m = (R600 - LSYP) - (R300 - LSYP) \tag{3}$$

$$YP = 2R300 - R600 = YP_m = 2(R300 - LSYP) - (R600 - LSYP) \tag{4}$$

Generally, *k* describes the thickness of the fluid and is thus somewhat analogous to apparent viscosity [92]. As the consistency index increases, the mud becomes thicker, based on [92]. *n* determines whether the fluid becomes less or more viscous as the shear rate increases, in accordance with [92,93]. The original expressions for *k* and *n* do not contain *LSYP* [83,84,92]. Here, the expressions for *k* and *n* of the developed real-time model take *LSYP* into account, and the *LSYP* term is a function of the viscometer readings at 3 and 6 rpm [4,84]. Thus, the modified k_m and n_m that contain the modified PV_m and modified YP_m considering the *LSYP* can be obtained from Equations (5) and (6) [2,84].

$$k_m = ((PV_m + YP_m) - (LSYP))(510)^{-n} = ((PV_m + YP_m) - (2R3 - R6))(510)^{-n_m} \tag{5}$$

$$n = 3.32log\left(\frac{(2PV + YP)}{(PV + YP)}\right) = n_m = 3.32log\left(\frac{(2PV_m + YP_m) - (2R3 - R6)}{(PV_m + YP_m) - (2R3 - R6)}\right) \tag{6}$$

In Equation (6), n_m is expressed as a function of PV_m, YP_m, and *LSYP* as defined by the equation. Substituting Equation (5) into Equation (1) and replacing *CCI* with the new parameter *HCI* yields Equation (7).

$$HCI = \frac{k_m \times AV \times MW}{5867} \tag{7}$$

Moreover, in Equation (7), the AV (as expressed in Equation (8)) is a drilling hydraulic parameter [29,84] that can be modified to include the effect of the hole inclination and the impact of the cutting rise velocity, cutting transport velocity, and cutting slip velocity defined by Equation (9). The modified annulus velocity (AV_m), which is equal to $V_{transport}$, is defined by Equation (9) as the summation of the velocity corrected for the wellbore inclination effect ($V_{corrected}$) and cutting slip velocity (V_{slip}) based on [45,84], where $V_{corrected}$ and V_{slip} are in (ft/min). V_{slip} can be calculated by considering the axial and radial cutting slip velocities with the influence of inclination and azimuth, as mentioned by Azar [32,39] and Robello [86]; therefore, $V_{slip} = V_{sa}\ cos(\alpha) + V_{sr}\ sin(\beta)$, where V_{sr} is the redial cutting slip velocity and V_{sa} is the axial cutting slip velocity. Moreover, in V_{slip}, the weight of cuttings and cutting diameter (inch) can be considered and calculated as $d_C = 0.2\left(\frac{ROP}{DSR}\right)$ in accordance with [45,84,94]. Finally, $V_{corrected}$, including annular, cutting, and transport velocities, and V_{slip} can be defined by Equations (10) and (11), respectively [2,45,84].

$$AV = AV_m = V_{transport} \tag{8}$$

$$V_{transport} = V_{corrected} - V_{slip} \tag{9}$$

$$V_{corrected} = \frac{24.5(Q)}{OH^2 - OD^2}\ cos(\alpha) + \left(\frac{60}{\left(1 - \left(\frac{OD}{OH}\right)^2\right)\left(0.64 + \frac{18.2}{ROP}\right)} + \frac{ROP\left(OH^2\right)}{60\left(OH^2 - OD^2\right)} \right) sin(\beta) \tag{10}$$

$$V_{slip} = \left(\frac{175\left(0.2\left(\frac{ROP}{DSR}\right)\right)\left(22 - \frac{MW}{7.481}\right)^{2n_m}}{(MW/7.481)^{n_m}\left(\frac{2.4V_{ann}}{OH-OD}\left(\frac{2n_m+1}{3n_m}\right)\left(\frac{200K_m(OH-OD)}{V_{ann}}\right)\right)^{n_m}} \right) \tag{11}$$

where Q is the mud pump flow rate (gal/min), OH is the hole size (in), OD is the drill pipe outside diameter (in) in the drilling-string design, α and β are the inclination and azimuthal directions of the hole (degrees), respectively, ROP is the drilling rate of penetration (ft/h), and DSR is the drill-string rotation (rpm). More importantly, the modified AV_m is applicable inside the drill pipe and in the annulus according to [83,86]. By combining Equation (8) to Equation (11), the transport velocity or the modified annular velocity can be expressed as indicated in Equation (12) [2,45,84].

$$\begin{aligned} AV_m = V_{transport} = & \left(\frac{24.5(Q)}{OH^2-OD^2}\ cos(\alpha) \right. \\ & + \left(\frac{60}{\left(1-\left(\frac{OD}{OH}\right)^2\right)\left(0.64+\frac{18.2}{ROP}\right)} + \frac{ROP\left(OH^2\right)}{60\left(OH^2-OD^2\right)} \right) \sin(\beta) \Bigg) \\ & + \frac{175\left(0.2\left(\frac{ROP}{DSR}\right)\right)\left(22-\frac{MW}{7.481}\right)^{2n_m}}{(MW/7.481)^{n_m}\left(\frac{2.4V_{ann}}{OH-OD}\left(\frac{2n_m+1}{3n_m}\right)\left(\frac{200K_m(OH-OD)}{V_{ann}}\right)\right)^{n_m}} \end{aligned} \tag{12}$$

where V_{ann} is expressed as a function of Q, OH, and OD by Equation (13), which is the original annular mud velocity applied in the vertical hole section based only on [83]. The modified annular velocity as defined in Equation (12) is a function of the flow rate and weight of the drilling fluid with cuttings, size of the drilled hole, outer diameter of the drill pipe, rate of penetration, drill-string rotation, modified plastic viscosity, modified yield point, viscometer reading at 3 rpm, viscometer reading at 6 rpm, wellbore inclination, and azimuthal directions [2,45,83,84]. Based on [2,9,86], the MW in Equation (7) is replaced by the equivalent mud weight (EMW) (Equation (15)), which accounts for the weight of the cuttings' influence and is a function of ROP, OH, and Q ((Equation (14)).

$$V_{ann} = \frac{24.5(Q)}{OH^2 - OD^2} \tag{13}$$

$$CA = \frac{0.00136ROP(OH)^2}{Q} \tag{14}$$

An equivalent mud weight (*EMW*) that incorporates the cutting accumulation (*CA*) is presented by Equation (15), based on [2,55,86].

$$EMW = MW(CA) + MW \tag{15}$$

Finally, the *HCI* is expressed as a function of PV_m, YP_m, *LSYP*, K_m, n_m, AV_m, and *EMW* calculated using Equations (3)–(6), (12), and (15) (see Figure 3).

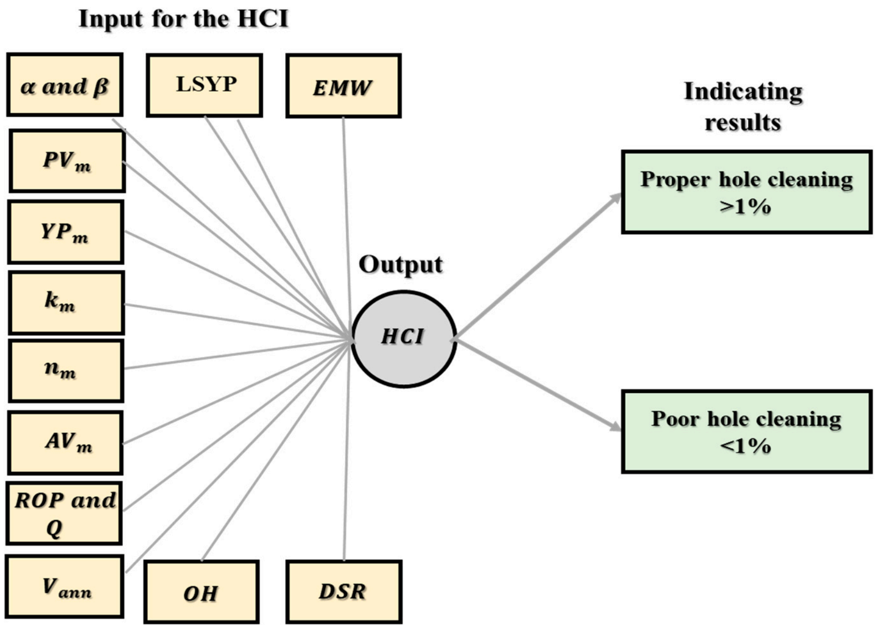

Figure 3. The input and output for the novel *HCI* model as a real-time evaluation indicating the hole-cleaning condition.

Equation (16) can be used to compute and finalize the modified *HCI* as a consequence:

$$HCI = \frac{K_m \cdot AV_m \cdot EMW}{5867} \tag{16}$$

The application of *HCI* to determine the status of hole cleaning during drilling is based on the classification of the *HCI* value. As the *HCI* parameter developed in this study is based on *CCI*, the classification ranges for the *HCI* parameter are based on the ranges of *CCI*, in accordance with [29]. *CCI* has two classification ranges of $CCI > 1$, which indicates proper hole-cleaning performance during drilling, and $CCI < 1$, which indicates insufficient hole cleaning [29]. Classification of *CCI* was also adopted for the *HCI* parameter [29]. An *HCI* value greater than 1 indicates proper hole cleaning, while an *HCI* value less than 1 indicates ineffective hole cleaning, which may lead to induced problems during drilling. More importantly, as illustrated in Figure 3, the *HCI* is a comprehensive metric and model that considers various parameters when assessing the effectiveness of hole cleaning. These parameters include rheological properties and density of the drilling fluid, as well as mechanical factors associated with drilling, such as well trajectory survey, mud velocities, rate of penetration, drill-string rotation, and cutting accumulation load. By considering these factors together, the *HCI* provides a more complete picture of the hole-cleaning conditions and can help identify potential issues that may arise during drilling. The use of the *HCI* in drilling operations can help optimize the drilling process and improve wellbore integrity. By monitoring the *HCI* and making adjustments to drilling parameters as needed, drilling teams can ensure that the wellbore is being cleaned effectively and that drilling operations are proceeding smoothly.

4. Field Applications Using the Novel Hole-Cleaning Index

The following flowchart exemplifies the estimation of the novel *HCI* model in real time (see Figure 4). Specifically, the flowchart demonstrates how the novel *HCI* model can be estimated in real time, with input data collected from various sources, including the monitoring operation, surface data, and operation report data. Three wells, namely Well-A, Well-B, and Well-C, were selected for this purpose. Furthermore, the performance of the *HCI* model was evaluated, and the importance, assumptions, and limitations of using the model in real-time are discussed. Finally, recommendations are provided to further improve the accuracy and efficiency of the model.

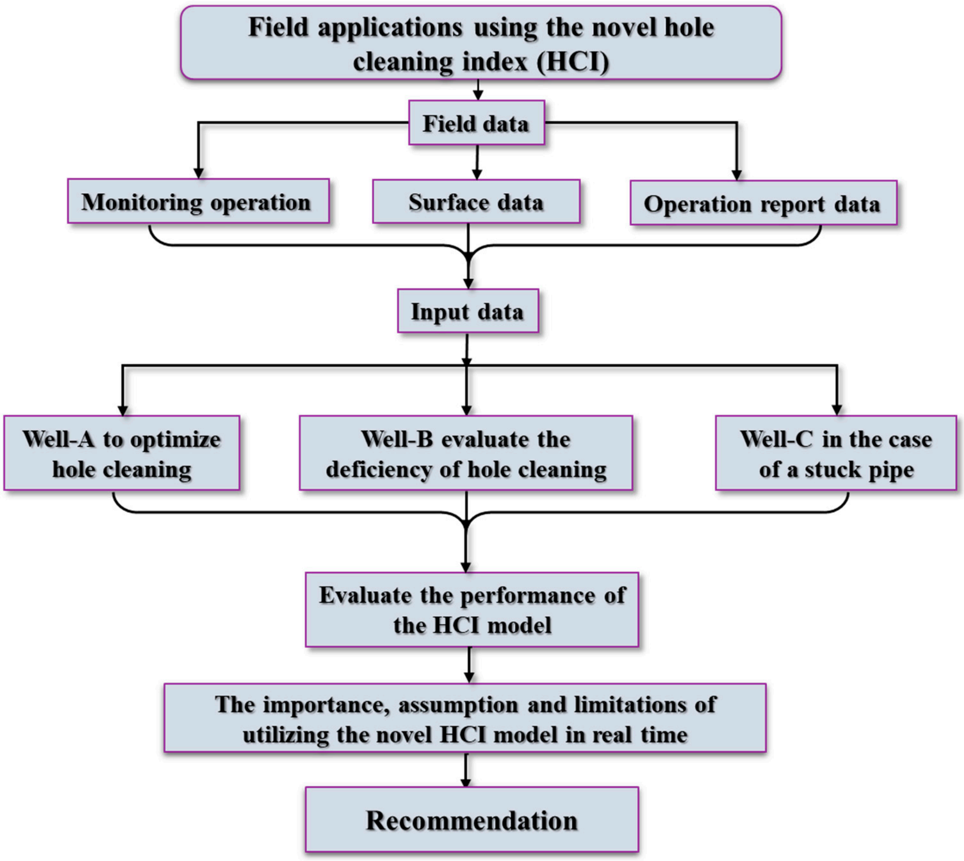

Figure 4. Flowchart to estimate the novel *HCI* model in real time.

4.1. Case Study and Data Description

Validation of the new *HCI* was demonstrated while directionally drilling 12.25″ intermediate sections of two offshore wells (Well-A and Well-B) and an 8.5″ liner section of another offshore well, Well-C, which experienced a stuck pipe incident. The 3 sections were highly deviated sections starting at 30 degrees and ending up nearing horizontal or 90 degrees inclination at the top of the reservoir. Figure 5 provides a clear schematic view of the three wells, including their respective sections. In the case of Well-A, the novel *HCI* model was utilized to evaluate the hole-cleaning conditions in the intermediate section at depths ranging from X100 to X1000 ft. For Well-B, the model was utilized to evaluate the hole-cleaning conditions at depths ranging from X100 to X520 ft. In the case of Well-C, which experienced a stuck pipe incident, the novel *HCI* model was utilized to evaluate hole cleaning in a stuck pipe incident due to the cutting accumulation at depths ranging from X1200 to X2200 ft. In this study, the formation and drilling cutting properties were carefully considered to ensure the effectiveness of the drilling process while utilizing the novel *HCI* model.

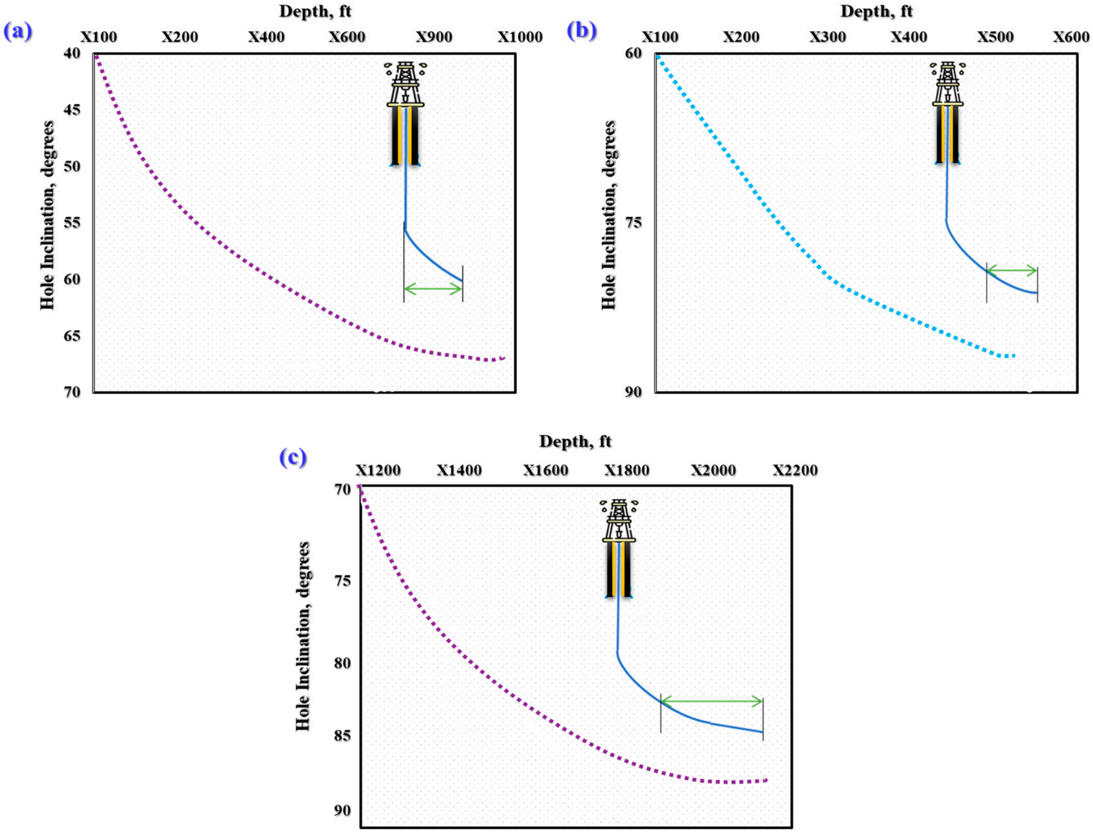

Figure 5. A schematic view of the wells and the sections used: (**a**) Well-A; (**b**) Well-B; (**c**) Well-C.

For Well-A and Well-B, the formation was composed of sandstone, limestone, and shale, with formation temperatures ranging from 140 to 155 °F. The formation porosity ranged from 0.15 to 0.25. The washout, which is the enlargement of the wellbore diameter due to the erosion of the formation, ranged from 10% to 30%. The properties of the drilling cuttings were also critical to the success of the drilling process. The density of the drill cuttings ranged from 20 to 24 ppg. The size of the drill cuttings ranged from 0.2 to 0.375 inches. Table 3 summarizes key characteristics of the drilled formations and cuttings produced during drilling of these sections. The two sections were drilled using an oil-based drilling fluid. For Well-C, the formation and drilling cutting properties were critical to the success of the drilling process. The formation temperature had a range of 155–175 °F, the porosity ranged from 0.10 to 0.15, and the washout had a range of 10–30%. The drill cuttings had a density of 20–24 ppg and a size of 0.15–0.3 inches. The section was drilled using an Innovert oil-based mud. Table 4 summarizes the drilling fluid properties used to drill these sections.

In addition to the properties of the formation and drilling cuttings, several important parameters were carefully monitored and recorded during the drilling operations to ensure the accuracy and effectiveness of the *HCI* model. These parameters included the rheological properties of the drilling fluid, mechanical drilling parameters, hole section directional survey, and hydraulic velocities. To facilitate the analysis and interpretation of the data, tables were created to summarize the various parameters recorded during drilling operations. The other rheological properties of the drilling fluid, mechanical drilling parameters, hole section directional survey, and hydraulic velocities required for calculation of the *HCI* are listed in Table 5, Table 6, and Table 7 for Well-A, Well-B, and Well-C, respectively. These data were crucial for the calculation of the *HCI*, which required accurate and up-to-date information on the position and orientation of the drill bit. Calculating the *HCI* played a critical role in maintaining effective hole cleaning and preventing stuck pipe incidents.

Table 3. Formation and drilling cutting properties for Well-A, Well-B, and Well-C.

Formation and Drilling Cutting Properties for Well-A and Well-B	
Parameter	**Value**
Formation lithology type	Sandstone, limestone, and shale
Formation temperature	(140–155) °F
Formation porosity	0.15–0.25
Washout	10–30%
Density of drill cuttings	(20–24) pounds per gallon (ppg)
Size of drill cuttings	(0.2–0.375) inches (in.)
Formation and drilling cutting properties for Well-C	
Parameter	**Value**
Formation lithology type	Sandstone, limestone, and shale
Formation temperature	(155–175) °F
Formation porosity	0.10–0.15
Washout	10–30%
Density of drill cuttings	(20—24) pounds per gallon (ppg)
Size of drill cuttings	(0.15—0.3) inches (in.)

Table 4. The drilling fluid characteristics for Well-A, Well-B, and Well-C.

The Drilling Fluid Characteristics for Well-A and Well-B	
Parameter	**Characteristic Range**
Oil-based drilling mud density	80 lb/ft^3
Oil ratio	(0.75–0.8)
Water ratio	(0.2–0.25)
Electrical stability	(400–600) Volts
Low-gravity solids	(2.5–5) Percent (%)
High-gravity solids	(10–15) Percent (%)
Marsh funnel viscosity	(65–75) Seconds (s)
Solid content	(15) Percent (%)
Mud solid control equipment efficiency	0.5
The drilling fluid characteristics for Well-C	
Parameter	**Characteristic Range**
Oil-based drilling mud density	88 lb/ft^3
Oil ratio	(60)
Water ratio	(40)
Electrical stability	(580–742) Volts
Low-gravity solids	(2.5–5) Percent (%)
High-gravity solids	(10–15) Percent (%)
Marsh funnel viscosity	(55–65) Seconds (s)
Solid content	(10) Percent (%)
Mud solid control equipment efficiency	0.5

Table 5. Well-A measured and calculated parameters.

Measured Parameters	**Minimum**	**Maximum**	**Average**
α, degrees	30	90	60
B, degrees	69	110	90
MW, pcf	80	80	80
PV, cP	30	32	31
YP, cP	23	24	24

Table 5. *Cont.*

Measured Parameters	Minimum	Maximum	Average
*R*3, cP	12	13	13
*R*6, cP	13	14	14
WOB, KIb	10	39	24
DSR, rpm	40	177	153
Q, Gal/min	590	1033	958
SPP, psi	900	2730	2411
Calculated Parameters			
LSYP, cP	11	12	12
K_m, cP	0.32	0.36	0.34
n_m	0.76	0.79	0.775
EMW, pcf	82	86	84
V_{ann}, ft/min	120	211	167
$V_{transport}$, ft/min	182	419	325
V_{slip}, ft/min	10	30	20
$V_{corrected}$, ft/min	170	440	300

Table 6. Well-B measured and calculated parameters.

Measured Parameters	Minimum	Maximum	Average
α, degrees	30	90	60
B, degrees	55	145	100
MW, pcf	80	80	80
PV, cP	30	30	30
YP, cP	23	23	23
*R*3, cP	11	11	11
*R*6, cP	8	8	8
WOB, KIb	22	39	30
DSR, rpm	50	190	171
Q, Gal/min	640	688	685
SPP, psi	1500	2730	3000
Calculated Parameters			
LSYP, cP	14	14	14
K_m, cP	0.23	0.23	0.23
n_m	0.82	0.82	0.82
EMW, pcf	82	87	85
V_{ann}, ft/min	130	140	140
$V_{transport}$, ft/min	109	390	248
V_{slip}, ft/min	10	35	22.5
$V_{corrected}$, ft/min	41.2	171	106

Table 7. Well-C measured and calculated parameters.

Measured Parameters	Minimum	Maximum	Average
α, degrees	22.9	82.75	42.83
B, degrees	53	115	84
MW, pcf	88	88	88
PV, cP	19	24	23
YP, cP	20	24	22
*R*3, cP	7	9	8
*R*6, cP	9	11	10
WOB, KIb	4.2	32.9	22.3
DSR, rpm	46.9	101.9	79.2

Table 7. *Cont.*

Measured Parameters	Minimum	Maximum	Average
Q, Gal/min	429	627	565
SPP, psi	1800	4062	3807
Calculated Parameters			
$LSYP$, cP	6	8	7.42
K_m, cP	0.364	0.55	0.41
n_m	0.655	0.736	0.713
EMW, pcf	88	91	89.7
V_{ann}, ft/min	222	325	293
$V_{transport}$, ft/min	44	208	124
V_{slip}, ft/min	19	147	60
$V_{corrected}$, ft/min	103	261	200

Moreover, a polycrystalline-diamond-cutter (PDC) drilling bit with 6 nozzles of 16/32″ size, hydraulic horsepower of 2.5–3.8, and total bit flow area of 1.17 square inches was employed to drill the sections under study in both wells. The other components of the bottom-hole assembly are listed in Table 8 for 12.25″and 8.5″deviated sections.

Table 8. Bottom-hole assembly (BHA) used to drill the 12.25″and 8.5″deviated sections.

Bottom Hole Assembly (BHA) for 12.25″						
Number of Joints	**Component**	***OD* (in)**	**ID (in)**	**Weight (lb/ft)**	**Connection**	**Length (ft)**
1	12.25 PDC drilling bit	12.25	2.78	150	pin 6-5/8 REG	0.89
1	*RSS* + motor	8	5.25	135	Box 6-5/8 REG	35.4
1	Bottom sleeve stabilizer	12.125	-	-	Box 6-5/8 REG	35.4
1	Float sub	8	3	147	Box 6-5/8 REG	2.82
1	String stabilizer	8	3	147	Box 6-5/8 REG	7.24
1	Measurements while drilling (*MWD*)	8	3.25	143	Box 6-5/8 REG	31.0
1	Downhole screen	8	3.25	143	Box 6-5/8 REG	6.20
4	Drill spiral collar	8	3	147	Box 6-5/8 REG	120.2
1	Drilling jar	8.12	2.75	132	Box 6-5/8 REG	21.8
2	Drill spiral collar	8	3	147	Box 6-5/8 REG	89.7
1	Cross-over	8	3	147	Box 4-1/2 REG	2.89
4	Heavy-weight drill pipe (*HWDP*)	5.5	3	49.3	-	120.3
					Total	473.73
Bottom Hole Assembly (BHA) for 8.5″						
Number of joints	**Component**	***OD* (in)**	**ID (in)**	**Weight (lb/ft)**	**Connection**	**Length (ft)**
1	8.5 PDC drilling bit	8.5	2.256	135	pin 6-5/8 REG	1
1	*RSS* + motor	6.75	2	120	Box 6-5/8 REG	35.36
1	Stabilizer	8	2.75			7
1	Float sub	6.75	3.25	132	Box 6-5/8 REG	2.83
1	Measurement while drilling (*MWD*)	6.75	3.25	132	Box 6-5/8 REG	35.35
1	Downhole screen	6.75	3.25	132	Box 6-5/8 REG	6.258
1	PBL circulating sub	6.75	2.75			6.5
5	Drill spiral collar	6.75	3.25	132	Box 6-5/8 REG	150.265
1	Drilling jar	6.625	2.625	132	Box 6-5/8 REG	20.25
3	Drill spiral collar	6.75	3.25	132	Box 6-5/8 REG	90.865
1	Cross-over	6.75	3	132	Box 4-1/2 REG	2.895
5	Heavy-weight drill pipe (*HWDP*)	5	4.27	26	-	150.356
					Total	508.929

4.2. Results and Analysis

4.2.1. The Application of the Novel *HCI* Model in Well-A and Well-B

The results of applying the novel *HCI* model were tested in two wells. The *HCI* system underwent testing and validation in the field. Implementing the new *HCI* model and its automation proved to be a valuable addition to drilling best practices, minimizing potential problems caused by insufficient hole cleaning. The results of the field application are explained below for Well-A and Well-B.

Well-A

The first case study considered in this work involves a well identified as Well-A, where the *HCI* was employed during drilling to optimize hole cleaning. The changes in *HCI* and other drilling parameters of this case are shown in Figure 6. In Well-A, during drilling at a depth of X500, the *HCI* value is more than 1.1, indicating that the wellbore is clean, without accumulation of any cuttings. The crew also did not observe any other indication of the accumulation of cuttings. At a depth of X760 ft, the *HCI* value begins to continuously decrease from 1.17 to less than 1.1 at a depth of X840 ft, as shown in Figure 6. As indicated, the decrease in *HCI* is not caused by an increase in *ROP*. Hence, the crew decided to clean the hole by increasing the pumping rate of the drilling fluid from 750 to 915 gal/min, which increased the *HCI* from less than 1.1 to more than 1.15.

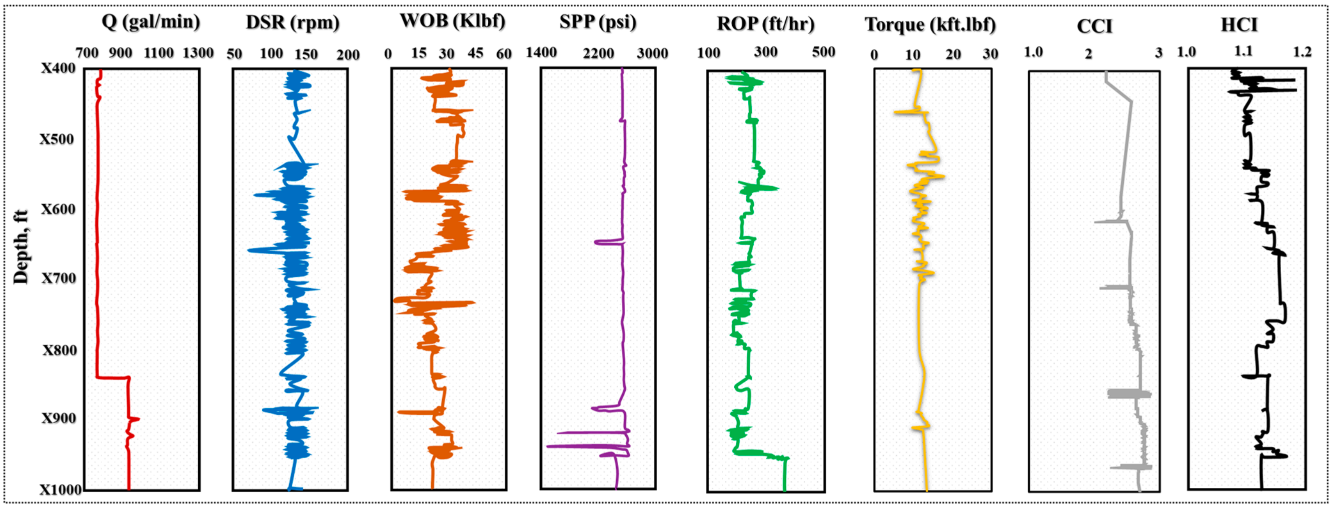

Figure 6. Changes in *HCI* and the drilling parameters for Well-A.

The crew also reported a decrease in erratic torque, which is an indication of removing the solids that had accumulated earlier at the bottom of the well. The crew members attempted to increase the drilling rate depending on the real-time estimation of the *HCI*. The changes in the drilling parameters and the associated *HCI* for this case are shown in Figure 7. The crew noted that the *HCI* indicates proper hole cleaning by evaluating the hole-cleaning conditions at depths between X120 and X150 ft. Thus, they decided to increase *ROP* by applying more weight on bit (*WOB*) to increase well drillability, as shown in Figure 7. When *ROP* is increased, the *HCI* decreases due to an increase in the concentration of cuttings in the wellbore, as indicated in Figure 7.

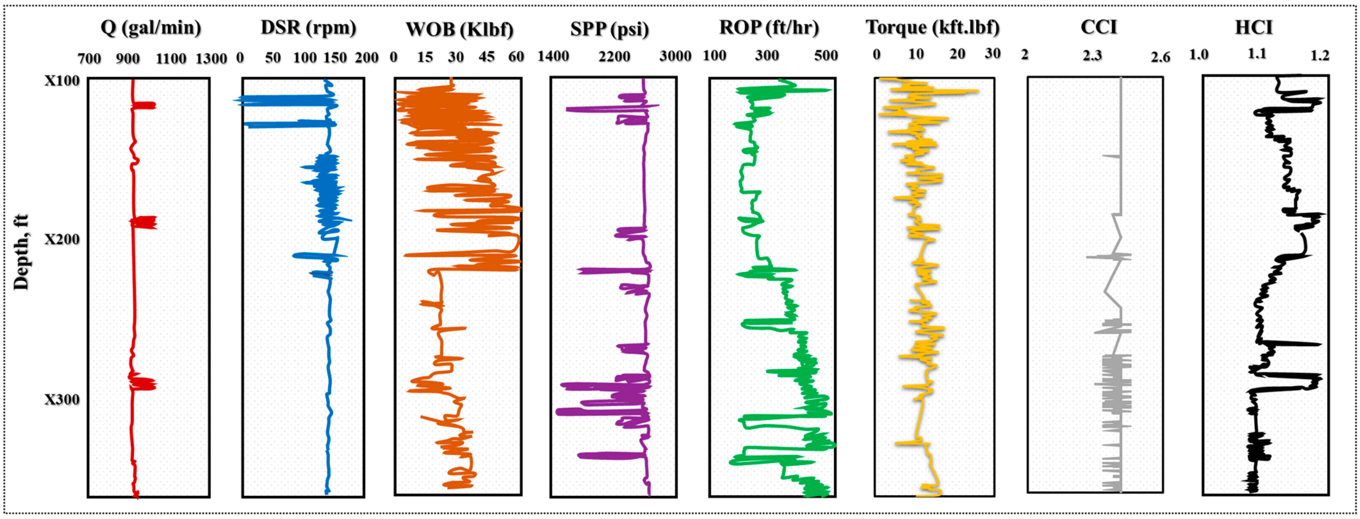

Figure 7. Changes in *HCI* and the drilling parameters for Well-A.

According to the driller, this trend also correlates with an increase in the drilling torque. As *HCI* values are still greater than 1.0 at a depth of ×300, which is the minimum limit for proper hole cleaning, the driller decided to maintain the same *ROP* of 280 ft/h for drilling deeper sections. The crew did not report any stuck pipe problems during drilling, and they were able to increase the drilling rate of this section based on the application of the *HCI*. More importantly, Figures 6 and 7 clearly illustrate the substantial discrepancy between the accuracy of the *CCI* and the novel *HCI* model in evaluating hole-cleaning conditions. The figures demonstrate that the *CCI* was not applicable and produced highly inaccurate results when compared to the highly accurate and reliable novel *HCI* model. In Figure 5, the *CCI* values ranged from 2.2 to 2.5 at depths from X400 to X430 ft, whereas the *HCI* values for the same depths ranged from 1.01 to 1.2. This significant difference highlights the limitations of the *CCI* and emphasizes the importance of utilizing the advanced *HCI* model for accurate and reliable hole-cleaning evaluation, particularly in deviated and horizontal wells.

Well-B

The second well of this study is identified as offset Well-B, where *HCI* was used to evaluate the deficiency of hole cleaning due to cutting accumulation and *HCI* was not employed for hole-cleaning efficiency. The drilling parameters and *HCI* are shown in Figure 8. The driller noted that the *HCI* is stable at approximately 1.13 for more than 100 ft, from X320 to X420 ft. At X420 ft, *ROP* decreases considerably from 300 to 200 ft/h due to drilling through a hard formation.

However, as the hole was appropriately cleaned, the driller decided to apply more *WOB* to increase *ROP* again to approximately 300 ft/h. The crew noted that the *HCI* gradually decreases when the *ROP* begins to increase, indicating the accumulation of cuttings. Hence, the driller was forced to increase the pumping rate of the drilling fluid from approximately 730 to almost 845 gal/min, as indicated in Figure 8, to maintain a clean hole while drilling at a higher rate without encountering any stuck pipe problems.

As the driller was aware that the bit would penetrate a soft formation at a depth of X160 ft, he decided to reduce *WOB* from 37 to 18 Klbf to prevent a significant increase in *ROP*. As indicated in Figure 9, even though *WOB* was significantly decreased to approximately $1/3^{rd}$ of its value, *ROP* in this soft formation increased only slightly from 200 to 240 ft/h. Even the *HCI* increased with this change, which did not lead to cutting accumulation.

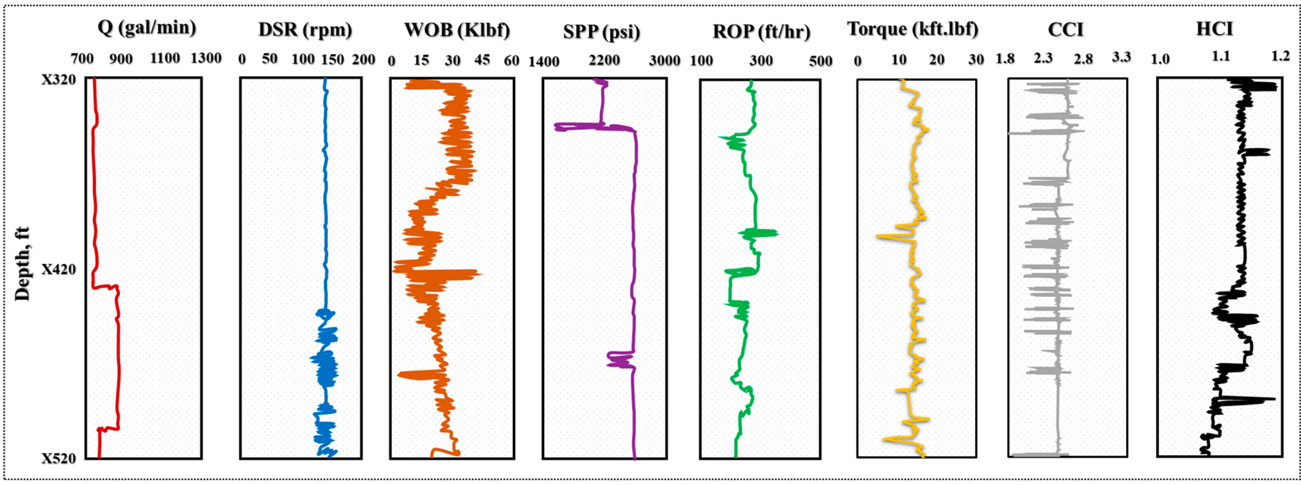

Figure 8. Changes in *HCI* and the drilling parameters for Well-B.

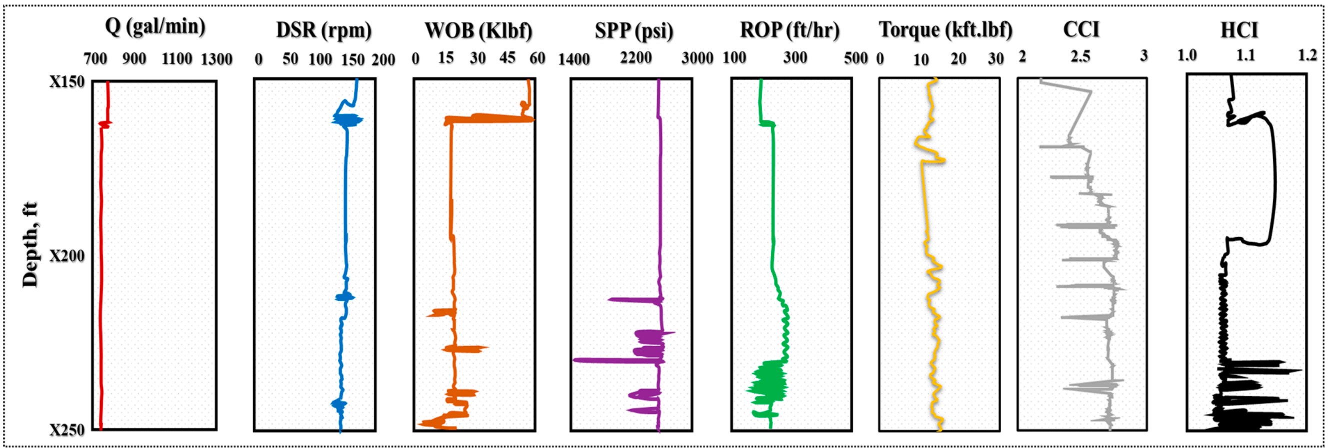

Figure 9. Changes in *HCI* and the drilling parameters for Well-B.

The drilling rate increases again from 240 ft to approximately 285 ft, accompanied by a decrease in *HCI* values from 1.14 to 1.06 without any change in *WOB*, owing to the penetration of another softer formation. Despite this decrease in *HCI*, the driller decided not to reduce *WOB* to decrease the drilling rate, as an *HCI* value of 1.06 is still in the safe zone to obtain appropriately clean holes. In addition to the discrepancies observed in Well-A, the *CCI* was also found to be unreliable in Well-B, producing inaccurate values when compared to *HCI*. Furthermore, it is crucial to take into account additional parameters such as hydraulic velocities to achieve a more comprehensive and accurate evaluation of hole-cleaning performance, particularly in deviated and horizontal drilling. The accurate measurement and tracking of hydraulic velocities are critical in ensuring the effective removal of drilling cuttings from the wellbore and preventing incidents such as stuck pipe incidents.

Table 9 summarizes the impact of the implementation of *HCI* on well performance when enhanced hole cleaning was performed in Well-A. The *HCI* had an average value greater than 1, and the *CA* was 0.024 in Well-A, whereas it was less than 0.04 in Well-B. The ultimate results show average *ROP* improvement in Well-A due to proper hole-cleaning achievement.

Table 9. Impact of employing *HCI* on well performance.

Items	Output	Minimum	Maximum	Average	Remark
Performance of Well-A employing *HCI*					
Items	**Output**	**Minimum**	**Maximum**	**Average**	**Remark**
1	*HCI*	0.8	1.9	1.5	Optimized hole-cleaning efficiency
2	*CA*	0.012	0.039	0.024	Smooth cutting accumulation in annulus removal due to optimized hole-cleaning efficiency
3	*ROP*	120	280	205	Optimized drilling performance due to proper hole-cleaning efficiency
Performance of Well-B without employing *HCI*					
Items	**Output**	**Minimum**	**Maximum**	**Average**	**Remark**
1	*HCI*	0.3	1.3	0.81	Improper hole-cleaning efficiency
2	*CA*	0.03	0.08	0.04	Low removal of cutting accumulation in annulus due to improper hole-cleaning efficiency
3	*ROP*	100	260	135	Low drilling performance due to insufficient hole-cleaning efficiency

4.2.2. The Application of the Novel *HCI* Model in Well-C in the Case of a Stuck Pipe

In deviated Well-C, the *HCI* model proved its effectiveness in evaluating stuck pipe incidents due to cutting accumulation. The third well of the study, which was identified as offset Well-C, was used to evaluate the performance of the *HCI* in these situations. The *HCI* was not employed for hole-cleaning efficiency in this well, but it was utilized to evaluate the stuck pipe incident caused by cutting accumulation. The drilling parameters and *HCI* values for Well-C are shown in Figure 10. As seen in the Figure 10, the driller noted an increase in cutting accumulation at depths ranging from X1200 to X1380 ft. Moreover, the driller observed that the *HCI* remained stable at approximately 0.55 to 0.8 for more than 700 ft, from X1520 to X2200 ft. Furthermore, at X1590 ft, the rate of penetration (*ROP*) decreased significantly from 200 to 100 ft/h due to the cutting accumulation, ultimately resulting in a stuck pipe incident. The driller was then forced to stabilize the pumping rate of the drilling fluid at almost 600 gal/min, as indicated in Figure 10. The *HCI* model was crucial to indicating and evaluating the hole conditions leading to the stuck pipe incident. By utilizing the *HCI* model, drilling teams can quickly identify and mitigate issues, preventing incidents such as stuck pipes and reducing nonproductive time, resulting in more efficient and cost-effective drilling operations. The effectiveness of the *HCI* model in evaluating stuck pipe incidents demonstrates its potential to significantly improve drilling operations.

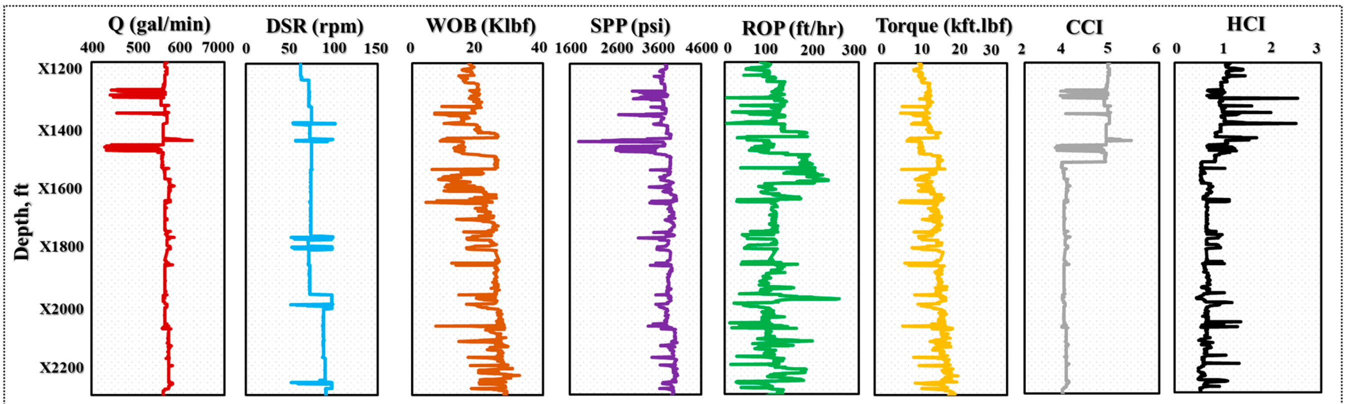

Figure 10. Changes in *HCI* and the drilling parameters for Well-C.

Table 10 summarizes the impact of the implementation of the *HCI* on well performance when hole cleaning during a stuck pipe accident in Well-C was evaluated. The *HCI* had an average value greater than 0.75, and the *CA* was 0.02 in Well-C.

Table 10. Impact of employing *HCI* on Well-C performance in the case of a stuck pipe.

Performance of Well-C Employing *HCI*					
Items	**Output**	**Minimum**	**Maximum**	**Average**	**Remark**
1	*HCI*	0.34	1.7	0.79	Improper hole-cleaning efficiency
2	*CA*	0.02	0.2	0.064	Low removal of cutting accumulation in annulus due to improper hole-cleaning efficiency
3	*ROP*	0.665	256	110	Low drilling performance due to insufficient hole-cleaning efficiency and stuck pipe

5. The Importance, Assumptions, and Limitations of Utilizing the Novel *HCI* Model in Real Time

The proposed *HCI* model sets itself apart from existing models that rely solely on laboratory data and lack the ability to provide real-time predictions. *HCI* utilizes a combination of real-time, surface, and operational data to produce instant predictions with high accuracy. This allows for the early identification and mitigation of abnormalities, leading to reduced drilling costs and operational time. In addition, the *HCI* model addresses the limitations of existing drilling operation models by providing instant predictions based on a combination of real-time, surface, and operational data. The automated flowchart shown in Figure 11 demonstrates the effectiveness of the *HCI* model in enhancing hole-cleaning performance and overall drilling efficiency. This innovative approach has the potential to significantly improve drilling operations, resulting in reduced costs and increased resource extraction. By leveraging the *HCI* model, drilling abnormalities can be identified and mitigated at an early stage, leading to reduced drilling costs and minimized operational time. As a result, the *HCI* model significantly enhances drilling performance efficiency.

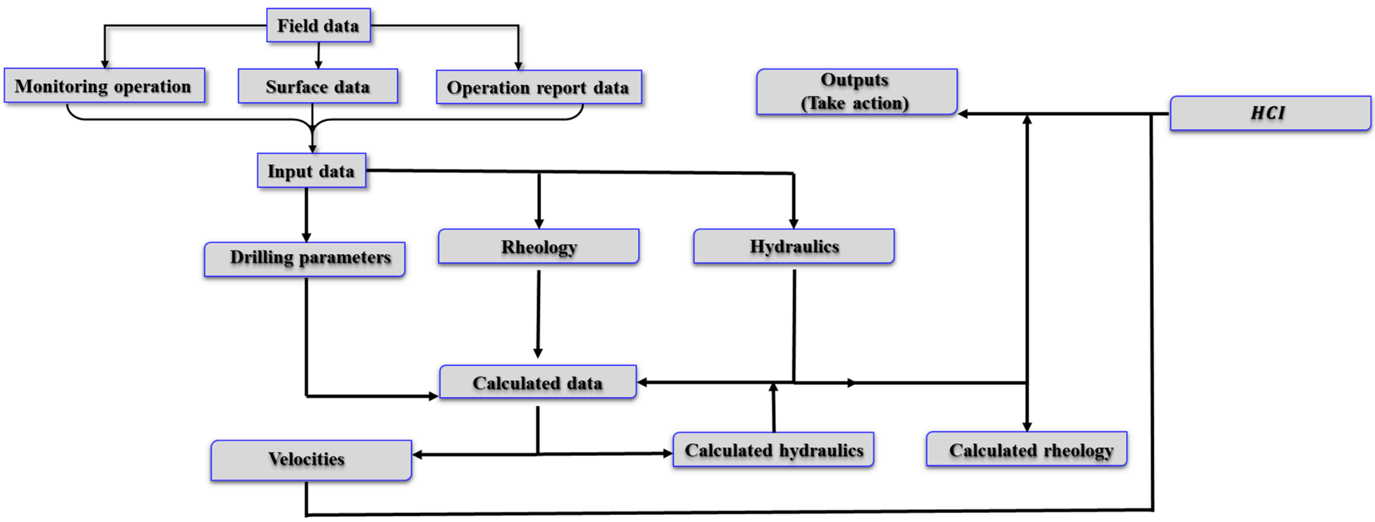

Figure 11. Field data were employed in an automated manner to analyze hole cleaning with the novel *HCI* model to increase drilling performance efficiency.

The *HCI* model has become an increasingly important index for hole cleaning in the oil and gas industry due to its ability to support consistent rig-site data capture and reporting across all operations, implement consistent data-quality methods and procedures, and support multiple units of measure. Additionally, the *HCI* enables operations engineers to remotely oversee drilling, provides accurate historical operations and performance data to well planners for statistical risk analysis, facilitates informed decision making, and enables live monitoring of drilling operation processes.

The *HCI* model also allows for the verification of best practices in drilling, drives continuous improvement across teams and basins, enforces procedural compliance, and elevates operational excellence. Furthermore, the *HCI* model ensures that data are always decision-ready, benchmarks drilling team performance, recognizes areas of improvement, and sets goals for footage per day, connections, and tripping. With analytics to minimize slide percentage, optimize drilling parameters, and mine offset wells for the best-performing BHAs, the *HCI* model contributes to safer, better, and faster drilling of wells. Additionally, it enables automated alerts and on-screen index indicators to avoid costly hazards, streamlines decision making, and accelerates *ROP*, while reducing drilling costs by leveraging next-generation directional guidance and rotary automation.

Despite its advantages, the *HCI* model also has limitations that must be taken into consideration. These include rig pump limitations. *Q* refers to the maximum flow rate that can be provided by the rig pumps. The top drive is another critical component that may place limitations on RPM. The design of the drill string and BHA can also impact the effectiveness of the *HCI* model, as can the performance of mud solid control equipment and mud system capacity. Finally, the quality and accuracy of sensor data acquisition can also affect the effectiveness of the *HCI* model, as any errors or inaccuracies in the data can lead to incorrect conclusions and decisions. Furthermore, the *HCI* model is based on certain assumptions, which include no total lost circulation incidents, no well control incidents, and no wellbore instability. These assumptions are critical to the accurate and effective use of *HCI* in the oil and gas industry and must be considered when applying the model to operational decision making.

6. Conclusions

In this study, a hole-cleaning index (*HCI*) was developed to optimize hole cleaning and positively impact well drilling ability by considering various parameters, such as drilling fluid properties, hydraulic velocities, and hole properties. Several points can be summarized as follows: the developed *HCI* model was rigorously tested and validated in the field in 3 wells, and the results demonstrated a remarkable improvement in well drilling performance by up to 50%. This significant improvement highlights the advanced capabilities of the *HCI* model and its ability to accurately evaluate hole-cleaning performance and optimize drilling operations.

- The limitations of the *CCI* were observed in all three wells, namely Well-C, Well-B, and Well-A, further emphasizing the unreliable nature of this model in evaluating hole-cleaning performance. In contrast, the *HCI* model proved to be highly accurate and reliable in all three wells. Moreover, accurate measurement and tracking of hydraulic velocities and the drilling fluid's rheological characteristics are crucial to achieving a more comprehensive and accurate evaluation of hole-cleaning performance, particularly in deviated and horizontal drilling. Furthermore, the *HCI* was applied in Well-C and showed a highly accurate result from its evaluation of the hole-cleaning condition.
- The implementation of the new *HCI* model can also lead to cost savings by preventing incidents such as stuck pipe and reducing non-productive time, resulting in more efficient drilling operations. Therefore, the adoption of the new *HCI* model can have a significant impact on drilling operations, promoting safer, more efficient, and more cost-effective drilling practices.

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Nomenclature

$R3$	3 reading revolutions per minute, cP
$R300$	300 reading revolutions per minute, cP
$R6$	6 reading revolutions per minute, cP
$R600$	600 reading revolutions per minute, cP
AV	average annular velocity, ft/min
CCI	carrying-capacity index
CA	concentration of cuttings in the annulus
K	consistency factor, cP
OD	drill pipe's outer diameter, inches
DSR	drill-string rotation, rpm
EMW	effective mud weight, pcf
n	flow behavior index
α	hole angle, degrees
β	hole azimuth, degrees
HCI	hole-cleaning index
$HWDP$	heavy-weight drill pipe
OH	hole diameter, inches
$LSYP$	low-shear yield point, cP
AV_m	modified annulus velocity, ft/min
k_m	modified consistency factor, cP
n_m	modified flow behavior index
PV_m	modified plastic viscosity, cP
YP_m	modified yield point, cP
MW	mud weight, pcf
MWD	measurement while drilling
PV	plastic viscosity, cP
Q	pump flow rate, gal/min
ROP	rate of penetration, ft/hr
rpm	revolution per minute, rev/min
RSS	rotary steerable system
d_C	the cutting diameter, inches
SPP	stand pipe pressure, psi
$V_{transport}$	velocity of cutting transport, ft/min
$V_{corrected}$	velocity of wellbore inclination effect, ft/min
V_{sr}	redial cutting slip velocity, ft/min
V_{sa}	axial cutting slip velocity, ft/min
V_{slip}	cutting slip velocity, ft/min
V_{ann}	annular velocity, ft/min
WOB	weight on bit, KIb
W	cutting weight, pcf
YP	yield point, cP

Appendix A. The Methodology of the Novel *HCI* Model

The following flowchart exemplifies how the novel *HCI* model surpasses the limitations of the old *CCI* model by incorporating a multitude of factors, including hydraulic velocities, rheological properties of drilling fluids, cutting properties, and effective mud weight. The comprehensive approach of the new *HCI* model ensures a more accurate and reliable analysis of hole cleaning, providing valuable insights that can enhance operational efficiency and reduce the risk of costly errors.

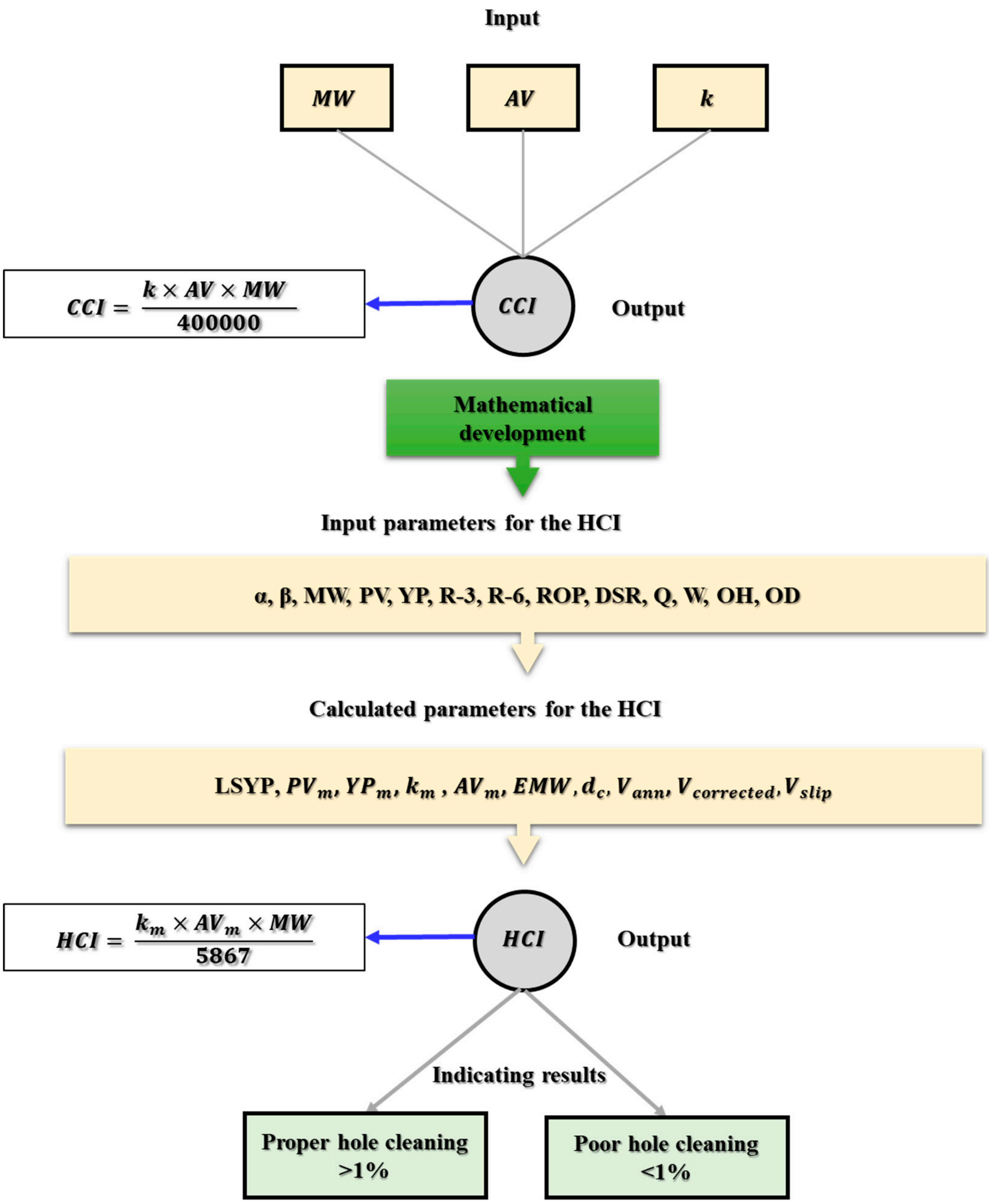

Figure A1. The Methodology of the Novel *HCI* Model.

Appendix B. Comparisons between the Novel *HCI* Model and *CCI*

Table A1. Comparisons between the novel *HCI* model and *CCI*.

HCI	*CCI*
Applied in vertical and directional wells	Only vertical
Includes comprehensive mud rheological properties such as PV_m, YP_m, *LSYP*, K_m, n_m, and *EMW* (applicable inside drill pipe and in annulus additionally)	Only *PV*, *YP*, *K*, *n*, and *MW* (only applicable inside drill pipe)
Includes V_{ann}, $V_{corrected}$, V_{slip}, and $V_{transport}$	Only V_{ann}
Includes mechanical drilling parameters (*ROP*, rpm, and *Q*)	Only *Q*
Considers well inclinations and azimuths	Does not consider
Includes cuttings features such as cutting weight and size	Does not include
Applicable with more real-time sensors such as *ROP*, *RPM*, *Q*, *EMW*, *MWD* survey, and caliper logs for real-time hole size diameter.	Only applicable with real-time sensors such as *Q* and caliper log
Includes cuttings concentration in annulus	Does not includes
Field applications in real time	Only experimental work
Able to identify hole-cleaning efficiency and deficiency	Not able to identify hole-cleaning deficiency.

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