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Mapping of Gross Heterogeneity of Mishrif Formation at West Qurna 1 Oilfield, Southern Iraq

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Abstract:

This study evaluates and maps the gross heterogeneity of the Mishrif Formation in the West Qurna-1 oilfield, southern Iraq, by counting the Lorenz coefficient (Lc) based on porosity, permeability, and thickness data from 99 wells. A custom Python script was utilized for data processing, and spatial interpolation was practiced using ordinary kriging in ArcGIS 10.8.2. The calculated Lc values range from 0.55 to 0.84, with an average of around 0.75, revealing a high to extreme degree of reservoir heterogeneity. Spatial distribution patterns indicate moderate heterogeneity in the northern sector, escalated heterogeneity in the central region, likely due to facies transitions, and extreme heterogeneity in the southern part, reflecting complex depositional environments and diagenetic alterations. These outcomes highlight the impact of heterogeneity mapping in optimizing well arrangement, enhancing sweep efficiency, and mitigating operational risks during reservoir development.

Keywords: West Qurna Oilfield, Reservoir Heterogeneity, Lorenz Coefficient, Coefficient of Variation, Spatial Distribution

Introduction:

Reservoir heterogeneity, a core hypothesis in hydrocarbon reservoir classification, signifies the spatial variability and internal complexity of key reservoir properties (Ahmed, 2010). Such variations demonstrate across multiple levels, ranging from microscopic differences at the pore and grain gradation to macroscopic divergences observed at interwell and field-wide scopes. Reservoir heterogeneity stems from diversified geological processes. The depositional environment plays a primary role by controlling the original distribution of grain size, sorting, and sedimentary structures. Post-depositional diversities, principally referred to as diagenesis, can further modify reservoir quality out of processes such as cementation, dissolution, compaction, and mineral alteration, markedly impacting porosity and permeability. Additionally, tectonic activities, including faulting, fracturing, and folding initiate structural discontinuances and create favored flow pathways within the reservoir (Ertekin et al., 2001). Generally, these geological processes result in variances in key reservoir properties, including porosity (the proportion of pore space within the rock), permeability (the rock's ability to transmit fluids), lithology (the type and composition of the rock), fluid saturation (the relative distribution of oil, gas, and water within the pore space), and capillary pressure (the pressure required to displace fluids in the pores) (Dake, 2001). Precise Recognition and description of reservoir heterogeneity are fundamental for dynamic reservoir management, simulation, and development planning. Heterogeneity considerably influences the performance of fluid displacement processes such as waterflooding, with a direct impact on sweep efficiency (Ahmed, 2010). This emphasizes the critical role of reservoir heterogeneity in dictating how effectively injected fluids can mobilize and recover hydrocarbons. Gross heterogeneity directly impacts fluid flow dynamics by energizing the movement and distribution of fluids within the reservoir. Large-scale heterogeneities also play a decisive role in signifying the overall recovery factor by governing flow pathways and easing hydrocarbon trapping mechanisms. Hence, an in depth understanding of these characteristics is crucial to prevent significant reductions in efficiency recovery (Lake & Society of Petroleum Engineers of AIME, 2014). From a field development point of view, gross heterogeneity directly impacts optimal well placement, completion design, and infill drilling strategies. Reservoir compartments with diverse connectivity need tailored strategies to elevate production and downsize interference between wells (Pyrcz & Deutsch, 2014).

A wide range of approaches ranging from statistical and geostatistical techniques to advanced numerical modeling and visualization tools, are adopted to evaluate reservoir heterogeneity in both clastic and carbonate settings. Each method provides critical understandings into the spatial distribution of key petrophysical properties, for instance, porosity is basically sectioned into total and effective types, with the distinction substantially influenced by clay content. In shaly formations, the effective porosity is conventionally lower than the total porosity (Mahdi et al., 2021). Other key reservoir properties include permeability, water saturation, and the net-to-gross ratio. These approaches allow engineers and geoscientists to better consider reservoir complexity and make more illuminated decisions regarding field development and management. One of the most acknowledged methods for quantifying reservoir heterogeneity is the coefficient of variation (CV), which exemplifies the ratio of the standard deviation to the mean of a reservoir property, such as permeability or porosity (Journel & Huijbregts, 1978). This simple yet robust metric equips a measure of variability within a dataset, with more elevated CV values specifying greater heterogeneity.

Along with the coefficient of variation (CV), the Lorenz coefficient and Lorenz plots are mostly used to estimate the distribution of permeability and flow capacity within a reservoir. A powerfully concave Lorenz curve ordinarily marks a high degree of heterogeneity, where a comparatively small portion of the reservoir volume accounts for an inappropriately large share of the fluid flow (Lake, 1989). These tools are substantial for determining flow-dominant zones and recognizing how heterogeneity affects reservoir performance. The Dykstra-Parsons coefficient is an additional conventional method, usually exploited in permeability data from well logs or core samples. It quantifies heterogeneity by appraising the spread of permeability values: values closer to zero suggest a homogeneous reservoir, while values progressing toward one signal extreme heterogeneity (Dykstra & Parsons, 1950). Although widely utilized, the method adopts a log-normal permeability distribution, which may not be held in geologically complex reservoirs.

The purpose of this study is to quantify and map the gross heterogeneity of the Mishrif Formation in the WQ oilfield employing the Lorenz coefficient. Mapping the spatial distribution of heterogeneity will support more dynamic reservoir management and facilitate in the optimal placement of production and injection wells. This, in the same way, is expected to enhance field development strategies, improve recovery efficiency, and minimize operational costs associated with production and injection jobs.

2. Material and methods:

2.1 The study area:

The West Qurna oilfield is located in southern Iraq (Fig. 1), near the city of Basrah and plus-minus 55 km south of the Rumaila oilfield, which is one of the largest in the world. It spans the Basrah Governorate and is segmented into two main sections: West Qurna Phase I and West Qurna Phase II. The field lies within the Mesopotamian Foredeep Basin, which accommodates some of Iraq's most abundant hydrocarbon reserves. The structural configuration of the West Qurna oilfield is part of an outstanding, elongated anticline trending approximately north–south, characteristic of many large hydrocarbon-bearing structures in southern Iraq. This anticline illustrates a gentle asymmetry, with the western flank dipping more steeply than the eastern limb and no major faulting observed within the Mishrif Formation. The structural top reaches an elevation of about 2160 m TVDSS (True Vertical Depth Subsea), reflecting the general tectonic inactivity that occurred in southeastern Iraq during the deposition of the Mishrif carbonates (Jassim & Goff, 2006).

Stratigraphically, the sedimentary succession in Iraq is subdivided into 11 megasequences (AP1 to AP11), as characterized by (Sharland et al., 2001, 2004). The West Qurna oilfield is originally situated within the Cretaceous stratigraphic interval, comprising most of AP8 (Late Tithonian–Early Turonian) and the totality of AP9 (Late Turonian–Danian). Megasequence AP8 encompasses several prolific reservoir units, such as the Yamama, Zubair, Mauddud, Rumaila, and Mishrif formations, while AP9 includes the Khasib and Sa'di reservoirs (Sharland et al., 2001). Amongst, the Mishrif Formation is the fundamental hydrocarbon-bearing unit, allocating more than 50% of the oil reserves and ongoing production in the field (Al-Ameri et al., 2011; Pitman et al., 2004).

The Mishrif Formation is interpreted as one of the considerable hydrocarbon reservoirs in southern and southeastern Iraq owing to its remarkable petrophysical and petrographic properties. Its extended distribution across many Iraqi oil fields further reinforces its value as denoting producing formation. The thickness of the formation mainly ranges between 150 and

200 meters, though it unveils considerable variation over different fields within the Mesopotamian Basin. Toward the eastern margin, in proximity to the Iranian border, the thickness provincially exceeds 350 meters (Hadeer Abdul Muttalib Al-Aradi et al., 2021; Saad M. Al-eisaa & Muwafaq F. Al-Shahwan, 2021). The formation deposited between the Lower Cenomanian (~98 Ma) and Middle Turonian (~93 Ma), lies at an average burial depth approaching 2400 m and reaches a thickness of approximately 200 m in the West Qurna region. It is conformably underlain by the Rumaila Formation and unconformably overlain by the Khasib Formation, exhibiting a second-order regressive cycle that terminated with regional exposure and non-deposition (Moore & Wade, 2013). The formation was deposited in a rimmed carbonate platform setting along the passive margin of the Arabian Plate, under warm, tropical conditions that preferred considerable carbonate productivity and sizable bioclastic accumulation (Al-Temimi & Read, 2012; Van Buchem et al., 2011).

The formation is made up of two third-order depositional sequences, each bound by regionally correlatively flooding surfaces (Sharland et al., 2001). Stemmed from sedimentological, petrographic, and reservoir features, the formation has been subdivided in the West Qurna oilfield into six stratigraphic members (from top to base): CRI, mA, CRII, mB1, mB2 Upper, and mB2 Lower (Al-Ameri et al., 2011) (Fig. 2). These subdivisions capture indicative lateral and vertical facies variations, actuated by relative sea-level fluctuations and carbonate platform dynamics during the Cenomanian–Turonian interval.

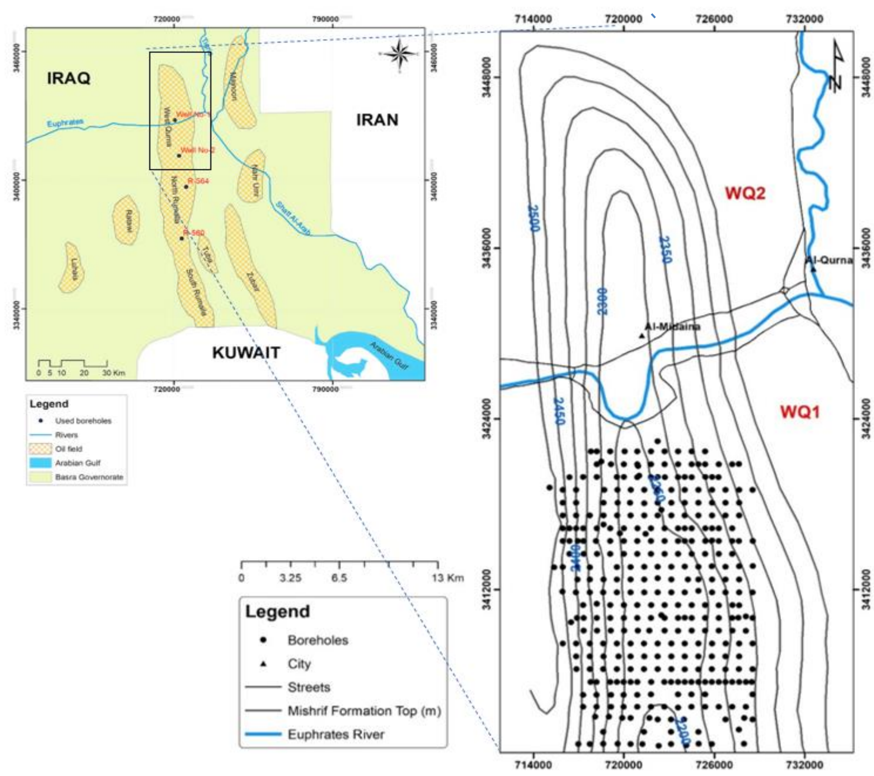

Fig. 1: Location of the WQ oilfield.

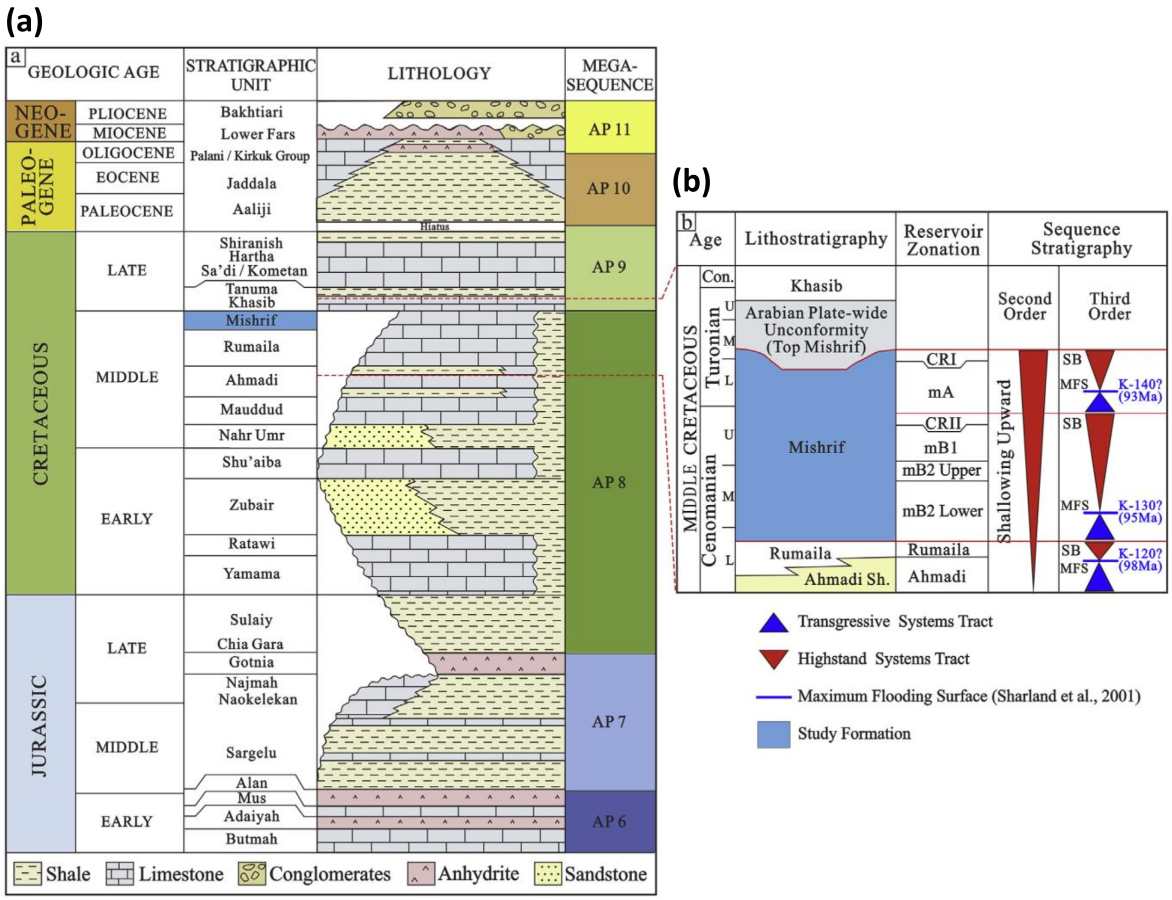

Fig. 2: (a) Generalized stratigraphic column of Jurassic – Cretaceous – Paleogene – Neogene in Iraq (After (Liu et al., 2018) adapted from (A. Aqrawi et al., 2010), (b) The sequence stratigraphy and reservoir zonation of the Mishrif Formation in the West Qurna oilfield).

2.2 Data and software used:

To figure the Lorenz Coefficient (LC) for the reservoir units of the Mishrif Formation, porosity (%), permeability (md), and thickness (m) data from 99 wells evenly distributed across the oilfield were exercised. The LC was computed for each of the three primary reservoir units, and their average was used to set spatial heterogeneity across the field following interpolation using the ordinary kriging technique. A custom Python script was improved to perform the heterogeneity calculations, while the geostatistical tools in ArcGIS 10.8.2 were utilized to interpolate the LC values and generate a surface map of gross heterogeneity.

2.3 L_c calculation:

The Lorenz coefficient (LC) is a widespread metric in reservoir studies for quantifying the extent of rock heterogeneity. The concept stems from the statistical analysis of rock property variability by (Law, 1944), who marked down that porosity generally follows a normal distribution, while permeability often demonstrates a log-normal distribution (Zahaf & Tiab, 2002). To describe this heterogeneity, the following formula is used (Fig. 3) (Schmalz & Rahme, n.d.; Tiab & Donaldson, 2015):

$$L_c = \frac{Area\ ABCA}{Area\ ADCA}$$

where the areas are stemmed from the cumulative plot of normalized flow capacity against cumulative pore volume.

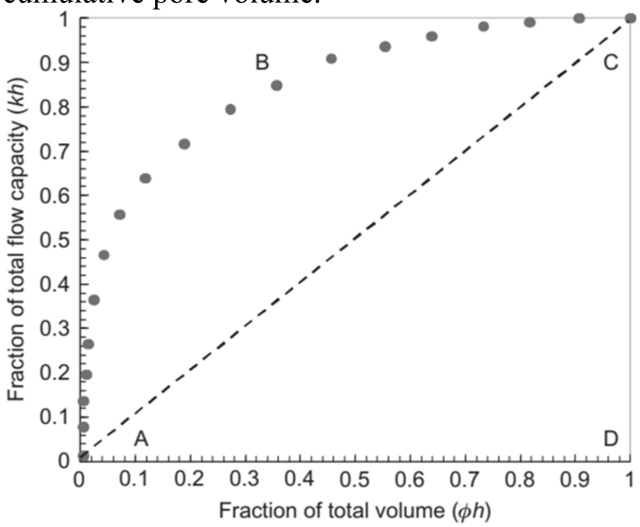

Fig.3: Flow capacity distribution (After (Dykstra & Parsons, 1950))

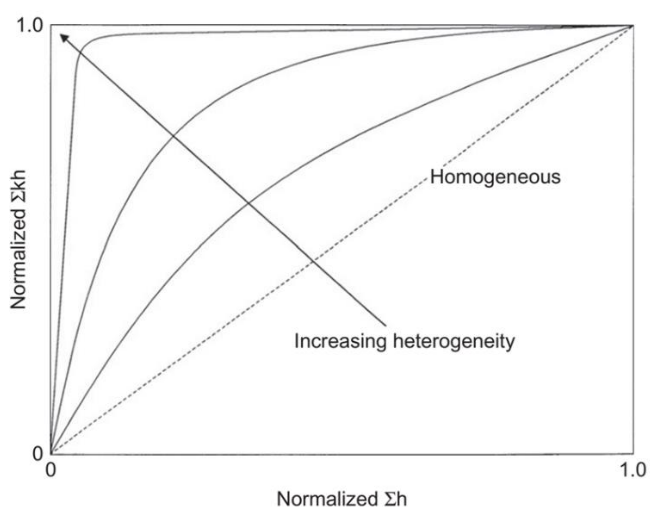

Fig.4: Normalized Lorenz curves show increasing reservoir heterogeneity (After (Ahmed, 2010))

The Lorenz coefficient (Lc) ranges from 0 to 1, where values arriving at 0 demonstrate a reservoir with a uniform permeability distribution, and values nearing 1 indicate high heterogeneity. Nevertheless, it is significant to identify that Lc is not a unique header of reservoir characteristics; different permeability distributions can introduce the same Lc value. This non-uniqueness may yield ambiguity in interpreting reservoir heterogeneity (Fitch et al., 2013).

The steps to calculate the L_c involve (Tiab & Donaldson, 2015): **(i)** Tabulate the thickness h, permeability k, and porosity φ of the reservoir unit. **(ii)** Sort the data in descending order of k.

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(iii) Compute the cumulate flow capacity $\sum(kh)_i$ and the cumulative pore volume $\sum(\phi h)_i$. **(iv)** Normalize these values to obtain the normalized cumulative flow capacity C_k, $C_k = \sum(kh)_i/\sum(kh)_t$, and the normalized cumulative pore volume C_ϕ, $C_\phi = \sum(\phi h)_i/\sum(\phi h)_t$. **(v)** plot C_k vs. C_ϕ on a 2 dimensions graph (Cartesian graph). **(vi)** Calculate the Lorenz Coefficient.

This method offers a simple yet valuable means of visualizing and quantifying reservoir heterogeneity. A high Lc value typically points out that fluid flow is dominated by a small portion of the reservoir, which can have fundamental implications for enhanced oil recovery (EOR) strategies and reservoir simulation efforts (Fitch et al., 2013).

3. Results:

The calculated Lorenz coefficient (Lc) values for the Mishrif Formation range from 0.55 to 0.84, with an average of 0.75, denoting a mostly high degree of heterogeneity. Only three wells—WQ-209, WQ-269, and WQ-283, characterizing approximately 2% of the total, exhibit Lc values below 0.6, signifying moderate heterogeneity. Most wells (about 77%) have Lc values between 0.6 and 0.8, categorizing them as highly heterogeneous. The remaining 21% of wells exhibit Lc values surpassing 0.8, manifesting extreme heterogeneity. This feedback confirms that the Mishrif Formation is predominantly typified by high to extremely high reservoir heterogeneity, which broadcasts important implications for fluid flow behavior, sweep efficiency, and the design of reservoir management strategies.

The spatial distribution of reservoir heterogeneity within the Mishrif Formation, as shown by the Lorenz coefficient, uncover noticeable variability across the oilfield. This heterogeneity is not uniformly distributed but is alternatively influenced by essential geological and petrophysical controls, including facies variations, depositional settings, and diagenetic processes. In the northern part of the field, Lorenz coefficient values are mainly lower, marking zones of moderate heterogeneity. These regions likely reflect more uniform depositional facies or well-connected pore networks, resulting in relatively consistent permeability and porosity distributions. Such conditions are advantageous to more foreseeable fluid flow and pressure behavior, which can enhance reservoir performance and improve sweep efficiency during production.

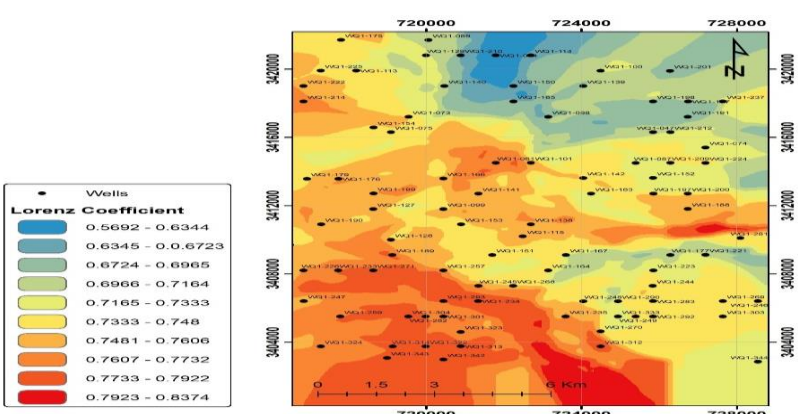

Fig. 5: Spatial distribution of Mishrif heterogeneity.

In the central section of the reservoir, Lorenz coefficient values indicate a remarkable increase, demonstrating a shift toward higher heterogeneity. This trend may result from transitions between varying lithofacies or structural complexities that disrupt both lateral and vertical reservoir continuation. Such zones are characterized by irregular distributions of petrophysical properties, which can result in localized high-permeability streaks or low-permeability barriers, thereby impacting reservoir drainage patterns and limiting effective pressure support.

Toward the southern part of the field, the elevated Lorenz coefficient values are noted reflecting areas of extreme heterogeneity. These zones are likely structured by complex depositional builds, sizable diagenetic alterations, and potential structural compartmentalization caused by faulting or stratigraphic pinch-outs. The existence of such heterogeneity generates robust challenges for reservoir management, including poor sweep efficiency, early water breakthrough, and complexity in maintaining uniform pressure support through injection strategies.

A table exhibits the Lorenz Coefficient values of the 99 studied wells.

Easting	Northing	Well Name	L_C
721805	3420801	WQ-034	0.728
725856	3416303	WQ-047	0.748
721806	3414501	WQ-061	0.777
719559	3417200	WQ-073	0.707
727200	3415401	WQ-074	0.729
719107	3416303	WQ-075	0.804
725406	3414500	WQ-087	0.677
723155	3417200	WQ-088	0.772
720066	3421697	WQ-089	0.758
720456	3411800	WQ-099	0.826
724506	3419900	WQ-100	0.644
722706	3414501	WQ-101	0.769
718206	3419901	WQ-113	0.701
722706	3420800	WQ-114	0.633
722500	3410200	WQ-115	0.615
719106	3410001	WQ-126	0.805
718650	3411800	WQ-127	0.751
720006	3420801	WQ-129	0.686
722706	3410900	WQ-138	0.775
724054	3419000	WQ-139	0.641

720480	3419000	WQ-140	0.753
721356	3412701	WQ-141	0.757
724055	3413607	WQ-142	0.772
722255	3419000	WQ-150	0.772
721708	3409105	WQ-151	0.751
725851	3413623	WQ-152	0.746
720906	3410901	WQ-153	0.728
718655	3416571	WQ-154	0.723
724256	3412701	WQ-163	0.838
723156	3408201	WQ-164	0.765
722256	3418100	WQ-165	0.757
720457	3413581	WQ-166	0.74
723607	3409102	WQ-167	0.688
717818	3421700	WQ-175	0.816
717757	3413565	WQ-176	0.756
726304	3409105	WQ-177	0.81
716937	3413568	WQ-179	0.684
726756	3418101	WQ-187	0.825
726751	3411801	WQ-188	0.756
719136	3409105	WQ-189	0.75
717303	3410901	WQ-190	0.744
726750	3417200	WQ-191	0.754
725861	3412700	WQ-197	0.84
725855	3418100	WQ-198	0.765
718655	3412706	WQ-199	0.744
726751	3412701	WQ-200	0.789
726288	3419888	WQ-201	0.835
716400	3414500	WQ-202	0.807
726301	3414501	WQ-209	0.571
720900	3420800	WQ-210	0.687
715950	3418100	WQ-211	0.792
726300	3416304	WQ-212	0.628
716850	3418100	WQ-214	0.668
727206	3409111	WQ-221	0.79

716850	3419000	WQ-222	0.818
725858	3408201	WQ-223	0.73
727200	3414500	WQ-224	0.812
717300	3419901	WQ-225	0.827
716848	3408204	WQ-226	0.756
717747	3408205	WQ-233	0.775
721351	3406401	WQ-234	0.788
723600	3405498	WQ-235	0.768
716400	3419900	WQ-236	0.774
727651	3418101	WQ-237	0.778
725848	3407300	WQ-244	0.79
721355	3407301	WQ-245	0.786
728551	3406401	WQ-246	0.719
716857	3406401	WQ-247	0.717
724053	3406398	WQ-248	0.727
725403	3405500	WQ-249	0.822
720450	3408204	WQ-257	0.812
717801	3405500	WQ-259	0.74
722252	3407300	WQ-268	0.681
727650	3406400	WQ-269	0.551
724501	3404631	WQ-270	0.756
718650	3408204	WQ-271	0.74
716400	3416300	WQ-279	0.751
716500	3409700	WQ-280	0.74
728101	3410101	WQ-281	0.739
720000	3405500	WQ-282	0.797
725851	3406401	WQ-283	0.566
724953	3406399	WQ-290	0.796
715951	3408201	WQ-291	0.781
725851	3405501	WQ-292	0.818
720450	3406400	WQ-293	0.783
720452	3405501	WQ-301	0.759
715950	3416300	WQ2-302	0.776
727651	3405501	WQ-303	0.849

719551	3405501	WQ-304	0.804
724500	3403750	WQ-312	0.767
720900	3403760	WQ-313	0.819
719150	3403750	WQ-314	0.644
720000	3403750	WQ-322	0.801
720900	3404600	WQ-323	0.791
717300	3403750	WQ-324	0.821
724951	3405501	WQ-333	0.794
720452	3402983	WQ-342	0.696
719006	3403073	WQ-343	0.796
728551	3402860	WQ-344	0.772

4. Discussion:

The Mishrif Formation is a complex carbonate reservoir whose heterogeneity originates from an aggregation of depositional architecture, diagenetic overprinting, and minor structural features. The computed Lorenz coefficient values, principally ranging from 0.6 to 0.8, and exceeding 0.8 in about 21% of the total number of studied wells, point out that fluid flow is extremely managed by relatively small, high-permeability zones. This results in irregular displacement fronts during production and increased risk of bypassed oil. Conversely, the northern portion of the field exhibits lower Lorenz coefficients, exhibiting more uniform depositional facies and better-connected pore networks. These conditions preserve more anticipated pressure distribution and are associated with feasibly higher sweep efficiency.

Coming near to the central sector, the observed increase in heterogeneity is probably attributable to lateral lithofacies transitions and minor stratigraphic pinch-outs, which originate local barriers and high-permeability channels, complexifying predictions of reservoir performance. The southern sector demonstrates the highest degree of heterogeneity, influenced by complex depositional settings, diagenetic alterations such as cementation and dissolution, and potential compartmentalization. These factors disturb permeability connectivity and heighten the risk of early water breakthroughs. This spatial variability emphasizes the importance of adopting reservoir-specific management strategies that take into consideration localized petrophysical variations. The incorporation of Lorenz coefficient analysis with geostatistical mapping equips a functional framework for visualizing and quantifying heterogeneity, consequently enhancing field development planning and decision-making.

5. Conclusions and Recommendations:

The Mishrif Formation at the West Qurna-1 oilfield displays evident gross heterogeneity, as characterized by Lorenz coefficient values ranging from 0.55 to 0.84, with an average of approximately 0.75. This heterogeneity is spatially variable, moderate in the northern sector, higher in the central region (probably due to lithofacies transitions), and excessive in the southern portion of the reservoir, where complex depositional processes and diagenetic overprinting predominate. These variations have a direct influence on fluid flow behavior, sweep efficiency, and overall recovery potential, confirming the dependency on detailed reservoir characterization. The integration of Lorenz coefficient analysis with geostatistical interpolation proposes valuable perception into the spatial distribution of heterogeneity, backing optimized well placement, minimized operational risk, and more applicable long-term production strategies.

Based on these findings and in support of more dynamic field development, it is recommended to integrate detailed facies and diagenetic models with spatial heterogeneity analysis to better forecast flow pathways and differentiate potential bypassed zones. Infill drilling and enhanced oil recovery (EOR) efforts should be concentrated on in the northern and central sectors, where heterogeneity is significant yet practicable, enabling more predictable sweep efficiency. Advanced reservoir simulation models incorporating Lorenz coefficient data should be performed to reinforce predictions of fluid distribution and pressure behavior across the field. Additionally, high-resolution core analysis, petrographic studies, and geophysical investigations, particularly in the highly heterogeneous southern sector, are mandatory for enlightening the understanding of heterogeneity drivers and informing targeted recovery strategies. Finally, heterogeneity maps should be constantly updated with new well data and production information to promote adaptive reservoir management and sustain optimal long-term performance.

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Declaration of Competing Interest:

The researcher declares that there are no known financial interests or personal relationships that could have influenced the work reported in this paper.

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