Hindawi
Journal of GeoEnergy
Volume 2023, Article ID 5547618, 11 pages
https://doi.org/10.1155/2023/5547618

Research Article

Hydrogeological Challenge for Coal Bed Methane (CBM) Production in Structurally Complex Reservoirs: Case Study for the Synclines of Umbita and Checua-Lenguazaque, Colombia

L. E. Rivera[1] **and J. E. Mariño**[2]

[1]*Aquifer Terranes, Calgary, Canada*
[2]*School of Geological Engineering, UPTC, Sogamoso, Colombia*

Correspondence should be addressed to L. E. Rivera; l.e.riverap@aquiferterranes.com

Received 12 August 2023; Revised 15 October 2023; Accepted 3 November 2023; Published 7 December 2023

Academic Editor: Mehdi Ostadhassan

Colombia is advancing toward pilot production of coal bed methane (CBM) at the Umbita syncline (US) and Checua-Lenguazaque syncline (CLS) in the Cundiboyacense plateau of the Eastern Cordillera. Although attractive, the development of CBM resources remains hydrogeologically challenging due to infinite acting aquifer (IAA) conditions, a sustainable production of ineffective water, which removal is critical to achieve methane desorption. Here, we assessed the implications of IAA on methane production prior to pilot development by comparing single-phase flow numerical simulations of the prospects. The results suggest IAA would extend the dewatering period in the Umbita syncline up to 20 years to potentially compromise the commercial recovery of methane. The Chequa-Lenguasaque, on the other hand, appears to have reached the phase of production of effective water; therefore, it is deemed as the most attractive prospect for pilot testing the production of CBM in Colombia.

1. Introduction

The demand for natural gas in Colombia for the period 2015–2030 projects a growth of 2.85% [1] that relies 100% on the reserves and production of conventional resources. The country has not yet reached commercial production from alternative sources like coal bed methane (CBM) to guarantee not only self-sufficiency but also the generation of foreign exchange from exporting surplus inventories.

Colombia is a significant coal producer and the largest in South America. Since 1981, coal production has grown from just under 4 million tons to a maximum of 90 million tons, achieved in 2017 [2]. Coal resources in the country are divided into 12 coal zones [3]. Almost all ranks of coal store gas, but the higher the rank, the larger the volume of methane is possible, mainly a result of thermogenic generation from burial and diagenetic processes [4]. The combination of high-gas potential and large coal emplacement indicates that Colombia has significant coal bed methane resources. To date, however, there has been little success in developing coalbed methane from either unmined or mined coal horizons.

The Government of Colombia, through the National Hydrocarbons Office (ANH) and the Colombian Geological Survey (SGC), has been evaluating the CBM potential of the country since 2013, which reserves are estimated between 44.95 and 112.89 trillion of cubic feet (Tcf) distributed in seven basins and 25 syncline and monocline structures [5]. Among these. the Checua-Lenguazaque syncline (CLS) and Umbita syncline (US) in the provinces of Cundinamarca and Boyacá (Figure 1) have been subject to several prefeasibility studies in preparation for the first pilot production of CBM testing in the country.

Resources of CBM in Colombia are typically found between 300 and 1,500 m deep [5–7], in which the hydrodynamic regime of neighboring aquifers and coal aquifers themselves is very active, imposing hydrogeological challenges to the removal of the ineffective water that precedes methane desorption [8].

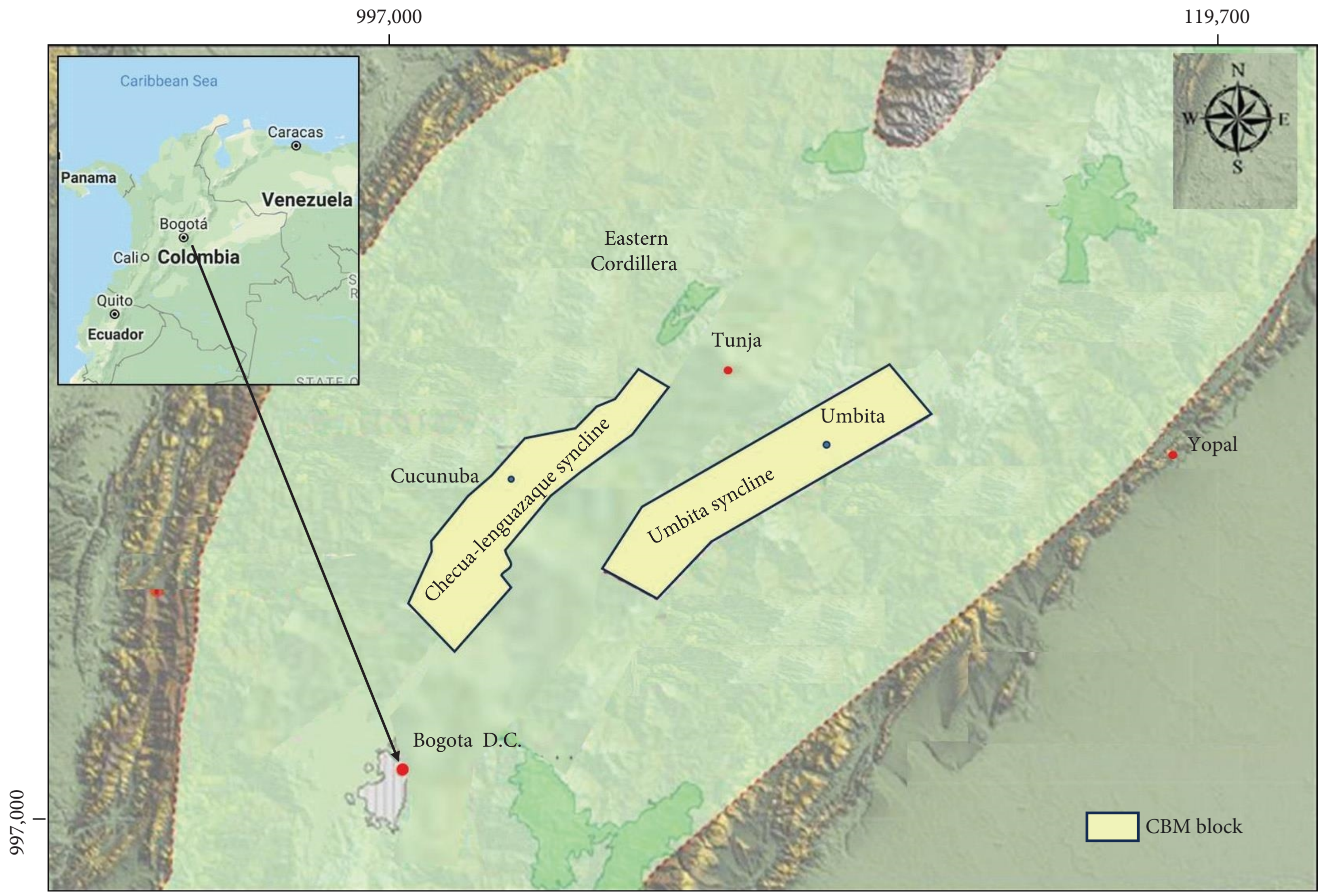

FIGURE 1: Location of the Umbita and Checua-Lenguazaque synclines. Adapted from GEMS [5], inset map by Google.

The hydrogeological regime in syncline CBM reservoirs is impacted by the infinite acting aquifer (IAA) type of flow, a sustainable groundwater yield without imminent flow barriers [9]. Development and severity of IAA is driven by saturation of methane, groundwater recharge, and generation of secondary biogenic gas. IAA is to inhibit the desorption of methane from coal during reservoir depressurization, extending the removal of ineffective water prior to reach the production stage. Removal of ineffective water is a stage of negative cash flow; therefore, the longer it takes, the higher the risk of rendering the production of methane at a commercial scale unfeasible.

This paper reviews the hydrogeologic challenge and current knowledge of the CBM resources at the US and CLS to evaluate whether IAA would be a potential limiting condition for methane desorption to progress toward pilot and commercial development. The assessment was carried out by comparing numerical simulations of single-phase flow, as it resembles the production of ineffective water, contrasted against limited recharge and biogenic gas generation data.

2. Hydrodynamics of CBM Reservoirs

Desorption is the driving force in the production of methane from coal deposits and is controlled by the hydrodynamic regime imposed by methane saturation, groundwater recharge, and generation of secondary biogenic gas. These same dictate the presence/absence of IAA.

2.1. Methane Saturation. The saturation history of a CBM reservoir is evaluated by methane isotherms to reveal the current levels of methane saturation. The saturated conditions are set at the maximum burial depth, where the content of gas occurs so that the coal is completely flooded with water to reach the maximum sorption capacity. Such conditions are represented by the isotherm at maximum temperature and burial in Figure 2.

During uplifting and exhumation, the porosity of the coal expands, and part of the absorbed gas is released to migrate toward neighboring formations and/or leak into the atmosphere through discontinuities, faults, and outcrops. At the same time, the pressure and temperature of the reservoir change, and so does the methane sorption isotherm, allowing the coal to retain more methane [12]. The pore system is then resaturated with water to configure reservoir conditions in an undersaturated state. The difference between the two isotherms represents the concentration of secondary biogenic gas needed to restore the reservoir to its original saturation state.

The saturation history throughout the evolution of CBM deposits to the current state provides essential information regarding the critical pressure to achieve methane desorption

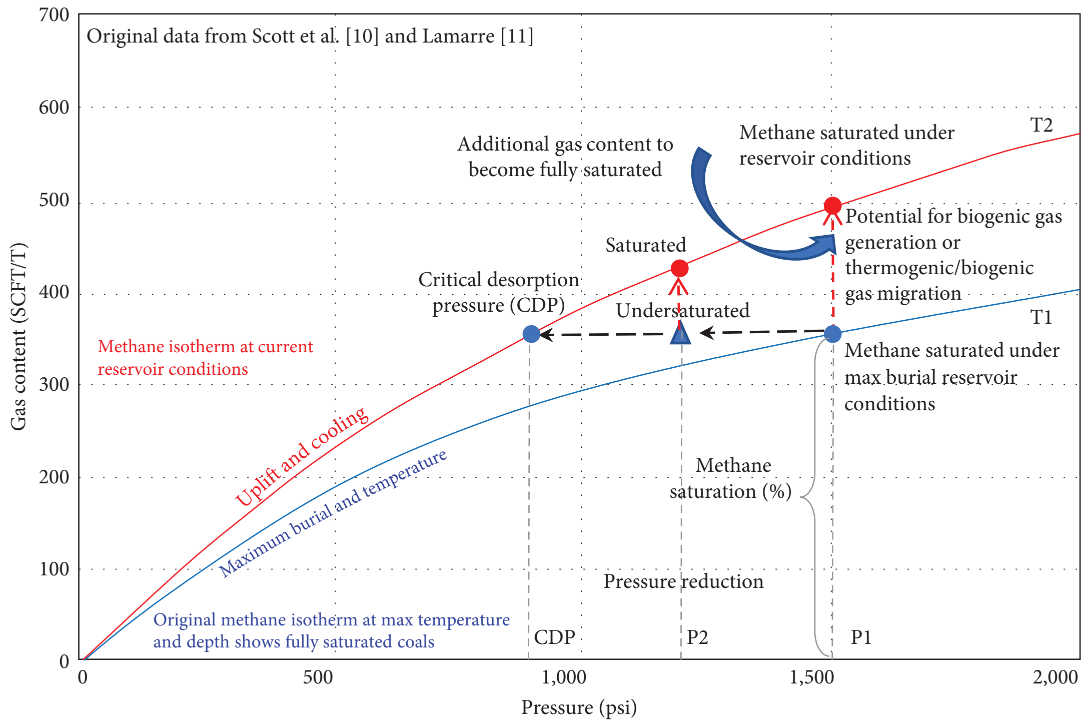

Figure 2: Methane sorption isotherms at reservoir conditions and maximum burial depth. After [10] AAPG © (1994), reprinted by permission of the AAPG, whose permission is required for further use, and [11].

(Figure 2), in other words, the minimum reservoir depressurization needed prior to initiating the mobilization of methane from the pores of the coal matrix to the cleats system by diffusion [13]. Thus, coals with gas content close to the sorption isotherm require a minimal level of depressurization (minimal drainage of ineffective water) to initiate desorption, resulting in rapid production and consequently faster return on investment [10]. Conversely, undersaturated coals require larger depressurization before methane desorption begins (Figure 2).

Under such a hydrodynamic regime, it can be then anticipated that undersaturated conditions will persist by the influence of original (meteoric) and induced recharge (cross-formational flow) from neighboring prolific aquifers, which is particularly true, as long as, the generation of secondary biogenic or thermogenic methane happen to be low, otherwise absent. Such conditions configure the IAA regime, which in turn will negatively impact methane desorption because of the sustainable input of ineffective water. On the contrary, secondary biogenic methane, a byproduct of bacterial metabolism and meteoric water, is adsorbed on to the coal matrix to displace the stored water partially or totally. Thus, the negative implications of IAA on the desorption of gas are to be attenuated, otherwise eliminated, while creating favorable conditions for methane production.

Despite their importance, the assessment of the saturation history of CBM fields in Colombia is yet to be addressed in depth in relation to the degree and severity of IAA. Some gas saturations measured in reservoirs across the country fluctuate between 30% and 70% to indicate they are expected to behave as undersaturated [14]. Others state that coal deposits are both saturated and unsaturated [5] but fall short in providing evidence. Moreover, some report supersaturated reservoir conditions that are physically improbable, e.g., at the CLS [6].

2.2. Biogenic Gas. Present-day biogenic gas in CBM reservoirs is rather considered secondary, generated by the metabolic activity of bacteria introduced into the reservoir by meteoric waters moving through permeable coal beds or other organic-rich rocks [10]; therefore, controlled by reservoir hydrodynamics.

The generation of secondary biogenic methane in the US and CLS was assessed by the isotopic relationship of δ^2H and δ^{13}C in methane following the approach proposed by [15]. The results suggest that most of the methane is thermogenic with a minor mix of thermogenic and biogenic. Such findings are inconclusive due to low sampling, lack of isotopic confirmation via acetate fermentation, and CO_2 reduction [16]. Further assessment of ^{13}C in dissolved organic carbon (IC), ^{18}O and ^{2}H isotopes in CMB waters to further differentiate multiple processes and paths during biogenic gas generation [17] were also missing.

Fail to assess the role of biogenic gas impacts the outcome of the desorption model and increases the uncertainty to successfully develop the resources since it will result in high-risk estimation of the amount of water to remove prior to reaching the production stage. Conversely, an accurate estimation of the potential of biogenic gas helps to timely assess the risk linked to the period of negative cash flow that precedes commercial production.

2.3. Groundwater Recharge. Hydrogeology research to establish the relationship between recharge and the potential for biogenic gas generation, the degree of gas saturation, and, ultimately, the presence of IAA conditions is also inadequate. COLCIENCIAS and the ANH through [18] completed a physicochemical characterization of the water associated with methane reservoirs in all coal provinces that included extensive sampling of surface and groundwater from both wells and underground mining works. The results inform in a general way on the basic physicochemical characterization of the waters associated with coals along with a preliminary geostatistical assessment of the geochemical similarity of hydrofacies by region. However, the nature and geochemical evolution of groundwater, essential for the modeling of methane entrapment and possible production implications, remains unsolved.

Devoted research to assess the role of recharge in secondary methane generation is also limited in the Colombian reservoirs. Mariño et al. [19] conducted a preliminary investigation of the hydrochemical conditions of groundwater and surface water as an attempt to establish the relationship between recharge and the high methane concentrations found in two exploratory wells with artesian flow attributes in the Umbita coal area in the province of Boyacá (Figure 1). Although the results report some physicochemical evidence that the nature of waters are likely associated with biogenic generation of methane, it falls short in confirming it, in part, due to low sampling and lack of isotopic assessment.

A broader hydrochemical assessment to include oxygen, hydrogen, strontium, and carbon stable isotopes from surface water, mine groundwater, and methane was completed as part of research efforts in the CLS [6]. It provided a more robust geochemical characterization of the coal connate water and its nature and evolution to differentiate both original (meteoric) and induced recharge (cross-formational flow) flow patterns within the coal seams. The stable isotopic data of oxygen (^{18}O), strontium ratio $^{87}Sr/^{86}Sr$, and $^{13}C_{inor}$ in surface and coal water suggest the recharge may play a role in the generation of incipient secondary biogenic methane in the southern part of the syncline.

3. Materials and Methods

The hydrogeological challenge for CBM production in the US and the CLS was assessed by simulating the likelihood of "infinite acting aquifer" (IAA) conditions [9] and the implications on the removal of effective water in the US and the CLS. The approach assesses the origin and hydraulic behavior of ineffective water [8], whose removal is, ultimately, the critical factor in the production of methane in CBM deposits. The IAA type-of-flow refers to the conditions of sustainable groundwater yield without imminent flow barriers. It depends on the hydrodynamics established by the recharge style, hydraulic gradient, and the confining attributes of the CBM reservoirs. The foundation for IAA was set by Devlin and Sophocleous [20] for depleting and sustainable groundwater systems in the budget water myth as follows:

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - Q_B = \Delta S = dV/dt, \quad (1)$$

where R_0 is the original recharge and D_0 is the original discharge at steady state condition, and ΔR_0 and ΔD_0 are the changes in original recharge and discharge induced by dewatering responsible for the change in storage ΔS or volume in time (dV/dt).

The IAA attributes are most prominent in symmetrical syncline-like structures with flanks exposed analog to a U-tube-like with open-ends hydraulic setting [9], illustrated in Figure 3. Under steady-state conditions (Figure 3(a)), prior to the reservoir depressurization ($Q_B = 0$), the change in storage (ΔS) is negligible or equal to zero, and the original recharge (R_0) is entirely meteoric. The original discharge (D_0), on the other hand, corresponds to the underground and surface flow exiting the system. Therefore,

$$\Delta R_0 = \Delta D_0 = 0, \quad (2)$$

$$R_0 = D_0. \quad (3)$$

As the pumping of ineffective water progresses, the reservoir develops transient conditions to eventually reach a new equilibrium or pseudo-state regime, as described in Equation (4). At this state, the yield of produced water (Q_B) triggers no further impact on groundwater storage, and the system becomes sustainable, driven by IAA conditions, since no imminent flow barriers are present; therefore, Equation (1) turns into Equation (5).

$$\Delta S = \frac{dV}{dt} \longrightarrow 0, \quad (4)$$

$$Q_B = \Delta R_0 + \Delta D_0. \quad (5)$$

The sources of water supporting Q_B are mainly the change in the original recharge (ΔR_0) [20], also called induced recharge to represent leaking water from prolific aquifers [13] or cross-formational flow [9, 21], and capture of the original discharge (ΔD_0) or amount of water intercepted by pumping from the underground discharge, the base flow from rivers and ultimately any surface water bodies. The IAA flow regime thus established is set to persist for as long as $\Delta R_0 + \Delta D_0$ is such that it minimizes the depletion of the stored water in the coal beds, e.g., dv/dt 0 (Figure 3(b)). Such a regime implies stability in the methane saturation to extend the depressurization period and further delay in reaching the critical desorption pressure.

A depleting system, on the other hand, is driven by the presence of flow barriers, which means that groundwater storage will eventually run out along depressurization. At this stage, the depressurization rate turns unsustainable, the reservoir enters a depletion mode, and IAA conditions preclude it. Depressurization later reaches the critical depressurization pressure (CDP) and production of methane stars (Figure 3(c)).

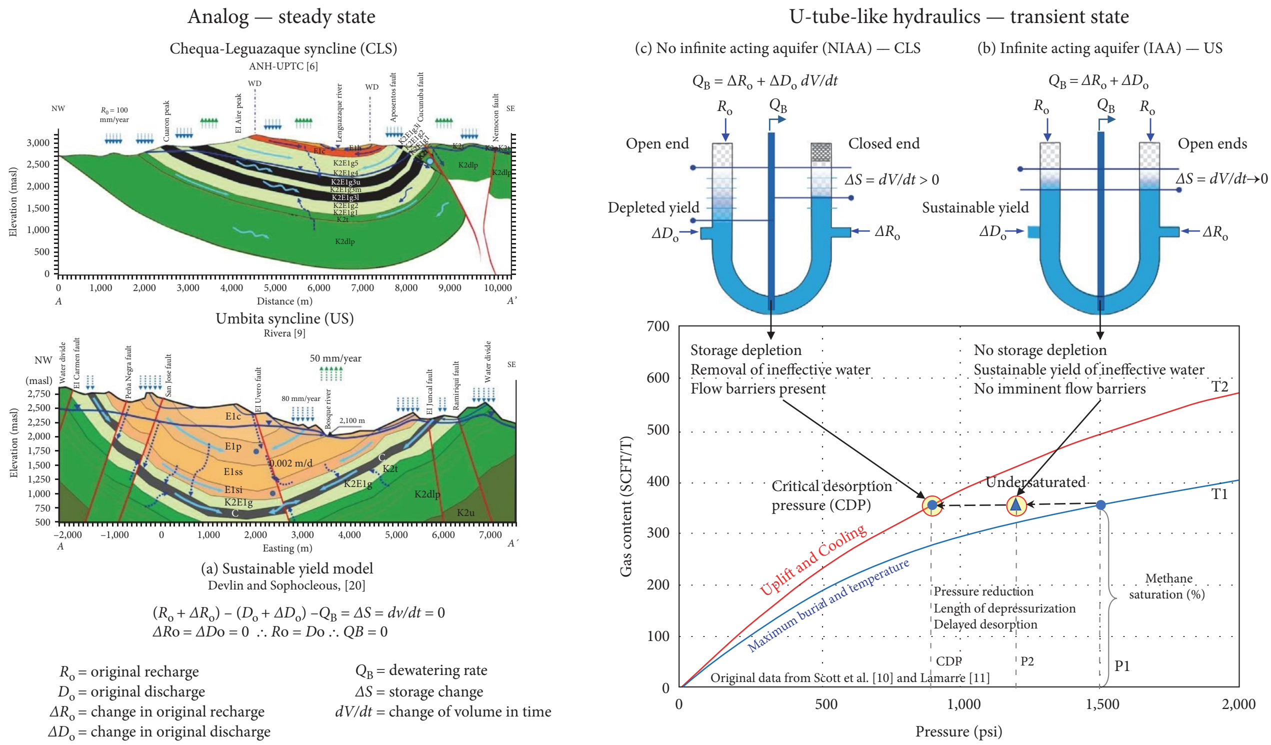

FIGURE 3: Hydrodynamics of symmetric and asymmetric synclines analogs to U-tube-like with open and closed ends hydraulic setting and relation to methane saturation. Adapted from [10] AAPG © (1994). Reprinted by permission of the AAPG, whose permission is required for further use, [9] and [6].

The most common approach to assess the implications of IAA in methane production comes from isotherm analysis and incorporates the degree of methane saturation, the magnitude of recharge, and estimation of the secondary biogenic gas generation as derived from lab and pilot testing. Alternate methods, such as single-phase flow numerical simulation, provide a back-of-the-envelope calculation regarding the dewatering efforts required to reach the CDP ahead of field and pilot testing in areas where lab and field testing are scarce. Is that lack of field data for the Colombian reservoirs that triggered the assessment of IAA via numerical methods and the central matter of development and discussion herein In addition to being a reliable tool for assessing the level of depressurization, the numerical methods have the advantage of predicting the switching time window from no CBM production to the production stage. Single-phase numerical flow simulations were carried out for the synclines of Checua-Lenguazaque in Cundinamarca [6] and Umbita in Boyacá [9] provinces, which are field analogs of structurally complex CBM reservoirs to assess the hydrogeological challenge imposed by IAA on methane production, while setting a benchmark approach to address the issue in structuraly simmilar reservoirs elsewhere.

4. Results

4.1. Umbita Syncline (US). The US is a faulted symmetrical structure with a northeasterly direction formed during the deformation and uplifting of the Eastern Cordillera. Multiple coal seams up to two meters thick in the Guaduas formation (KTg) configure the CBM deposit, overlain by the Socha Inferior (Tsi) and Picacho (Tpi) aquifers, and the underlying Labor-Tierna aquifer system (K1) (Figure 4). The flanks dip approximately 45°; therefore, the syncline is classified as an open fold [9].

The type-of-flow in the US is gravitational, with the local component mimicking the topography and the intermediate flowing parallel to the dip confined within the aquifer layers and coal seams. The resulting flow pattern is, therefore, linear convergent with recharge in the outcrop of the flanks and discharge in rivers and streams running at the lows of the structure along the hinge (Figure 5). The hydraulics thus established is an analog to a U-tube with open-ends-like flow settings [9] illustrated in Figure 3(b) to configure the most extreme conditions that would restraining methane production.

The saturation of methane in the US would be rather inferred low due to the little potential for biogenic gas generation that is suppressed by the high groundwater potential, an active original recharge (R_0) acting on the flanks of a symmetric structure and the induced recharge (cross-formational flow) across the hydrostratigraphic units. There are no records of major methane explosions in underground mining works in the region, which suggests that the original concentration of methane is rather locked within the coal seams by the sustainable groundwater yield imposed by IAA.

The results of the single-phase flow simulation confirm the likelihood of IAA in the US that would likely impact the ability to produce methane in a commercial fashion. The

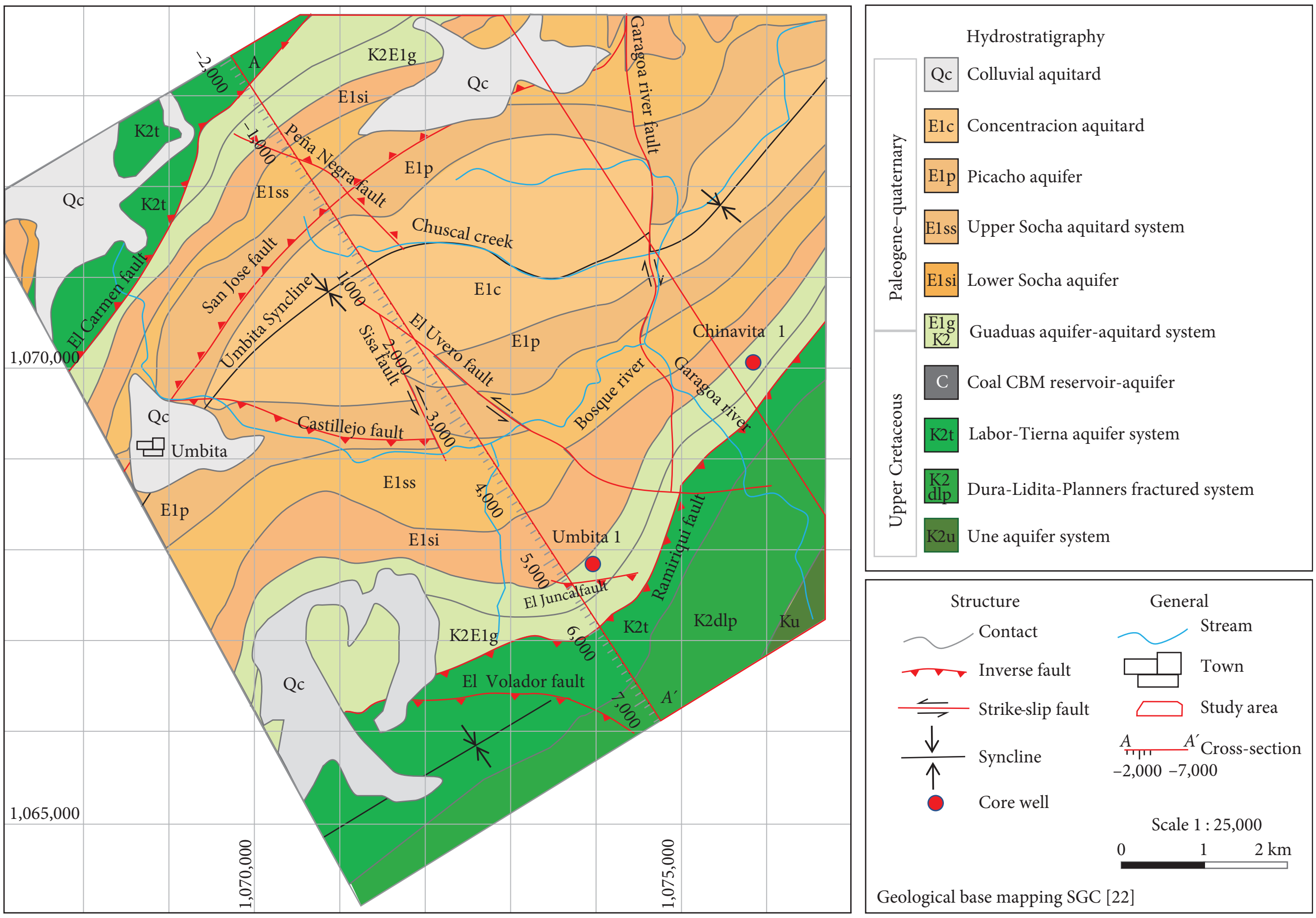

FIGURE 4: Hydrostratigraphic map of the Umbita syncline [9]. Modified from Elsevier© (2019). Reprinted by permission.

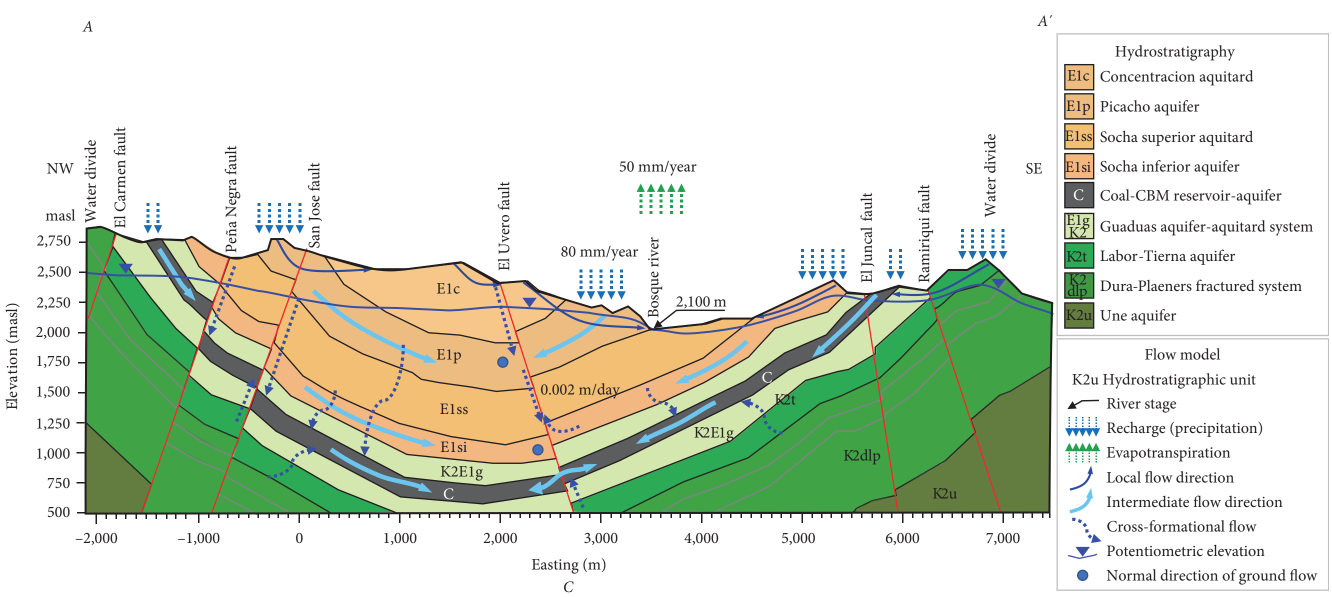

FIGURE 5: Conceptual flow model for the Umbita syncline [9]. Modified from Elsevier© (2019). Reprinted by permission.

evidence to support IAA is the anticipated production of ineffective water at a sustainably yield under extreme depressurization regimes for extended periods of time. The simulated dewatering through 15 pumping wells and a total rate greater than 7,000 m^3/day suggests that significant depletion to remove the ineffective water—drawdown > 100 m—would only occur after 20 years of operation (Figure 6). Mass balance calculations indicate that the source of the sustainable yield

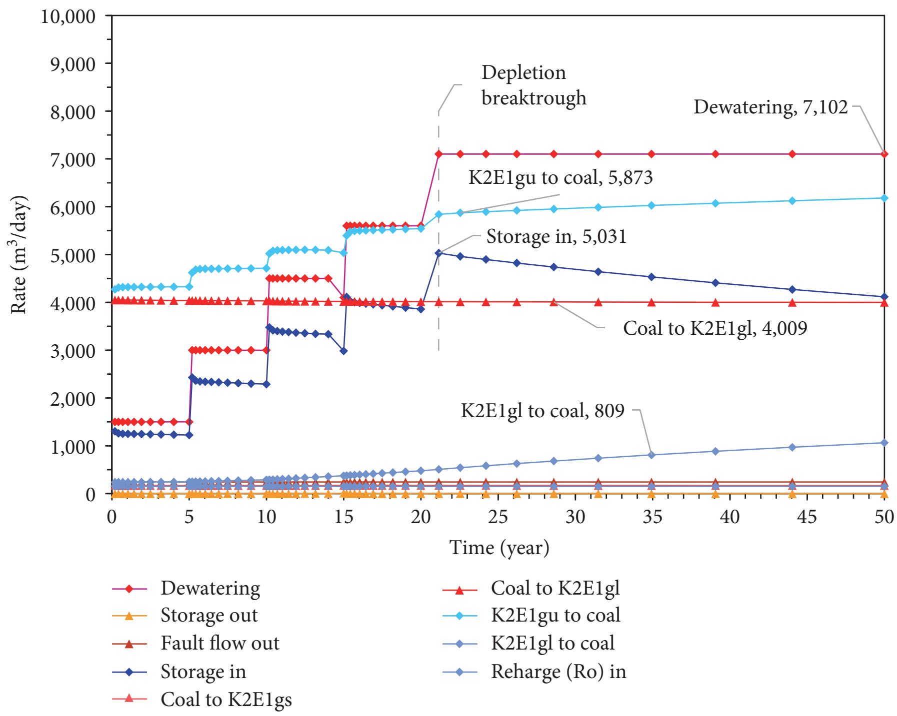

FIGURE 6: Mass balance for the depressurization model of the Umbita syncline [9]. Modified from Elsevier© (2019). Reprinted by permission.

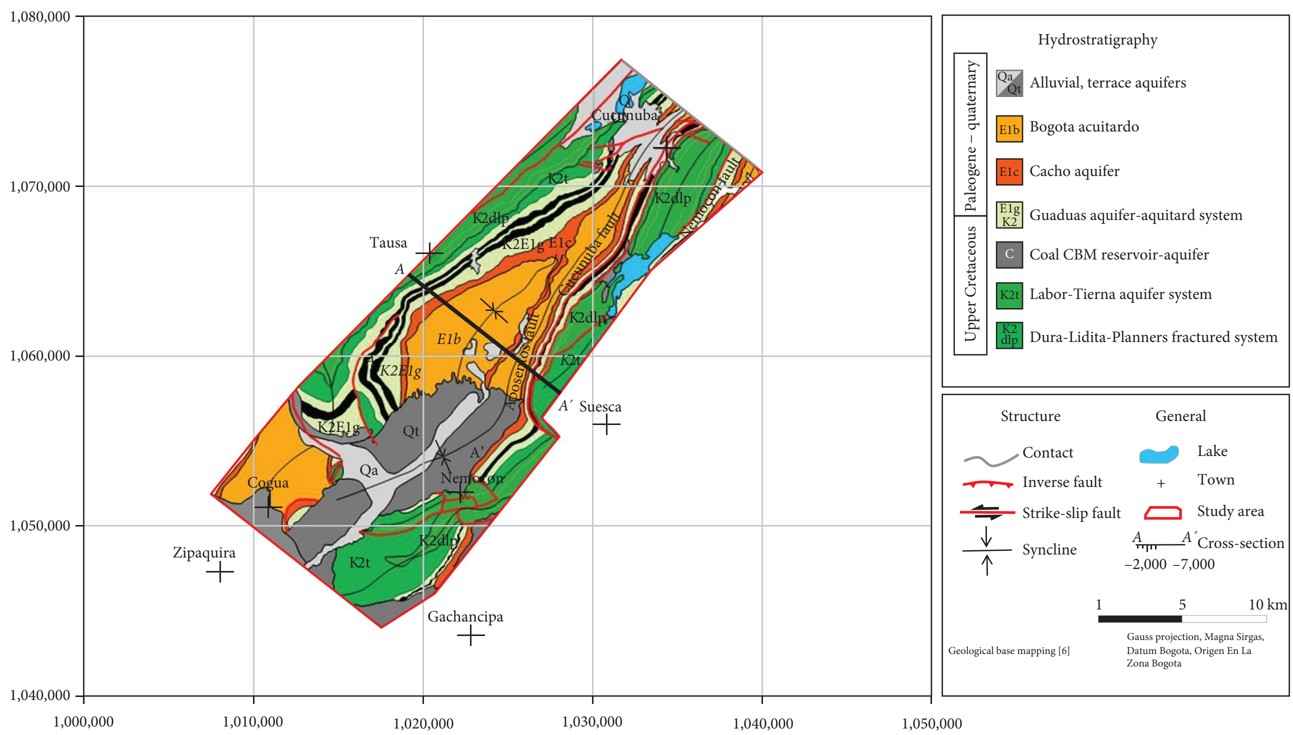

FIGURE 7: Hydrostratigraphic map of the south Chequa-Lenguazaque synclyne. Modified from [6].

would be not only the original recharge (ΔR_0) and its change (ΔR_0) expressed by the sotorage in, but captured discharge (ΔD_0) or crossformational flow, drawing water from neighbor aquifers at the top and bottom as stated in Equation (5).

4.2. Checua-Lenguazaque Syncline (CLS). The tectonic and structural domains of the CLS are part of a mountain block with high slope flanks forming linear escarpments product of differential erosion. The structure has a SW–NE direction

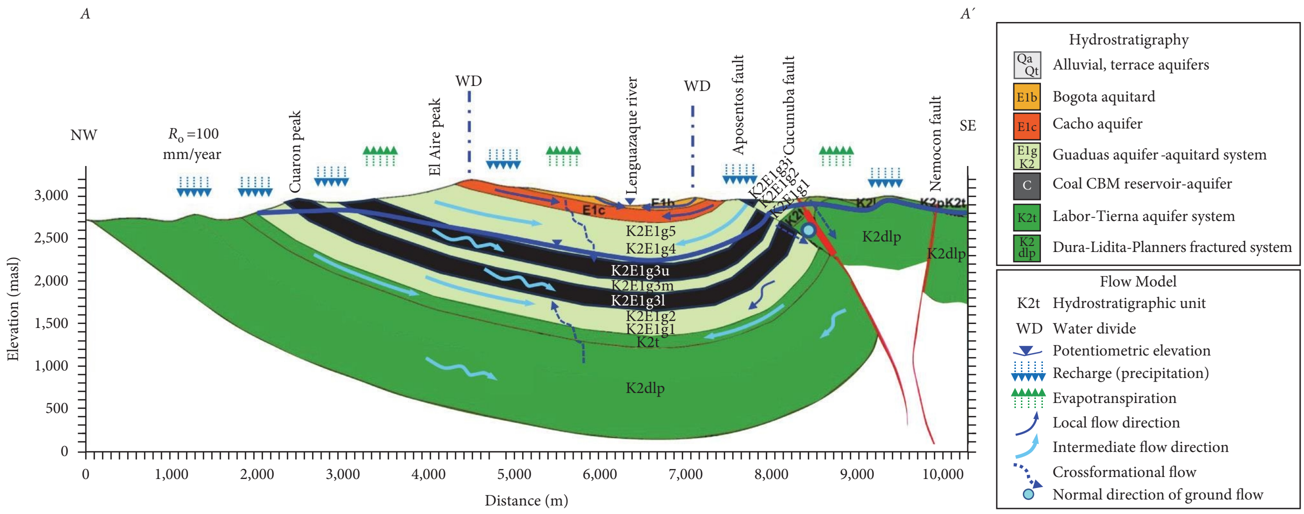

Figure 8: Conceptual flow model for the south Checua-Lenguazaque syncline. Modified from [6].

from Zipaquira to Samaca regions in the Cundinamarca and Boyacá provinces, with its axis aligned to the course of the Guachaneca, Lenguazaque, and Checua rivers (Figure 7). The reservoir consists of multiple coal seams of the Guaduas Formation (K2E1g) with a maximum thickness of 2.20 m confined to the top by intervening aquitards of the upper Guaduas Formation and overlain by the prolific aquifers of Cacho (E11) and Regadera (E2r). At the bottom, the reservoir is confined by the intervening aquitards of the Lower Guaduas and the Labor-Tierna aquifer system (K2t). In the south (sector Tausa-Suesca), the syncline is an open fold with flanks dipping 20° west and 15° east, whereas in the north (Cucunuba-Samaca sector) it is closed with flanks dipping 70° east and 85° west (Figure 8).

Unlike the US, the CLS is asymmetrical, eroded at lower elevations in the western flank, and truncated by the Aposentos and Cucunuba faults in the eastern rise to configure an analog of a U-Tube with the west end open-like hydraulic setting. Therefore, a low-pressure-field, high-water potential regime is expected to drive the current coal depressurization and methane desorption observed in the underground mine works in the west flank and the high-pressure-field, low-water potential responsible for gas trapping in the core and the east flank of the structure.

Recharge of the coal seams within the aquifer-aquitard system of the Guaduas Formation in the southern sector of the CLS occurs mainly lengthways the western flank. It is prolific with long residence time and likelihood to trigger bacterial metabolic activity to generate biogenic gas as interpreted from ^{13}C and the ratio $^{87}Sr/^{86}Sr$ isotopic data. Although not a dominant process, the isotope ratios of δ^2H and $\delta^{13}C$ measured in methane from coal samples of underground mining works in the west flank further support the generation of secondary biogenic gas. The recharge in the eastern flank, on the other hand, is constrained by the limited hydraulic communication of the coal seams to the surface, constrained by the seal of the Aposentos and Cucunuba faults (Figures 7 and 8). That is, unlike the west, the coal seams in the east flank maintain the original saturation and entrapment of methane during the uplifting of the cordillera; therefore, greater saturation of methane is expected from the core of the syncline to the east enhanced by the high-pressure field and low water potential [23].

The southwestern closure of CLS lies unconformable with quaternary deposits of the Bogota flats northeast of the Cogua town, configuring a seepage boundary. The same occurs west of Cucunuba, where the CLS was broken by flexural deformation, later incised by local alluvial deposits (Figure 7). Therefore, the flow pattern is anticipated to be bilinear convergent toward the hinge of the syncline, turning divergent to the northeast and southwest to discharge in the quaternary aquifers of Cucunuba-Ubate and Cogua-Nemocon.

The numerical assessment of IAA for the CLS was carried out in the south sector between Cucunuba and Nemocon to simulate present-day depressurization induced by more than 50 years of underground mining, simulated by means of 17 synthetic pumping wells distributed across the structure to resemble the current mine drainage. The wells were set up to draw water from the coal seams in the upper Guaduas K2E1g3s-Manto Grande-Ciscuda and lower sK2E1g3i-Manto Vidriosa, Cisquera, Siete Bancos at a constant rate of 100 m^3/day for 50 years.

The results indicate that at current mining conditions, the coal seams in the upper segment of the Guaduas formation K2E1g3s would have reached up to 13 m drawdown equivalent to a depressurization of 127 kPa approximately nearby the well Cucunuba 3 (Figure 9(a)). Likewise, the coal seams in the lower segment (K2E1g3i) would have depleted a bit less down to 10 m, equivalent to a drop-in reservoir pressure of 100 kPa (Figure 9(b)). Such a pressure drop is interpreted to be equivalent to the critical desorption pressure, given the fact that methane is currently produced in underground mining works and is responsible for the frequent explosions in the region. The simulations also indicate a lower level of depressurization of the eastern flank, which

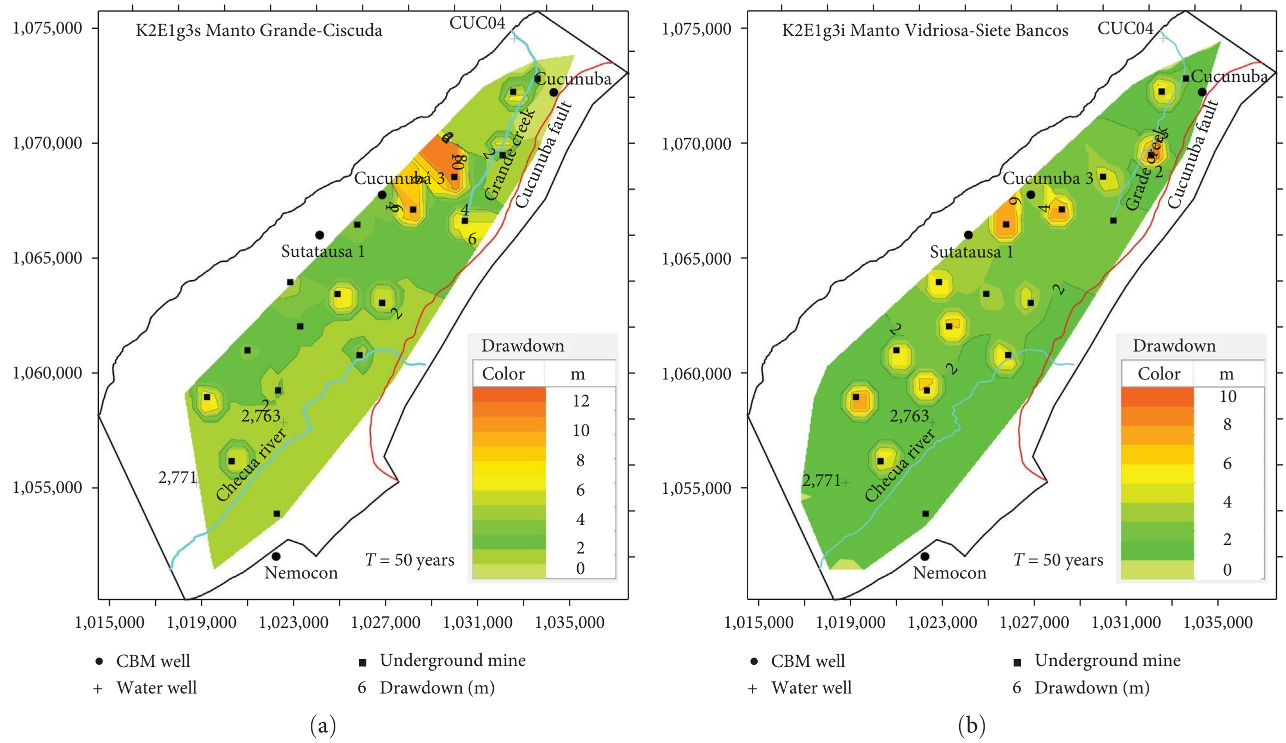

Figure 9: Present day depressurization model for the south Chequa-Lenguazaque syncline [6].

confirms that CBM entrapment is hydrodynamically active from east to west, matching the U-Tube with a closed-end-like hydraulic setting in Figure 3(c).

5. Discussion

IAA is the out-of-sight-out-of-mind fact behind unsuccessful CBM prospects worldwide. Responsible for the high water cut–low methane ratio, IAA frequently turns drastic enough to trigger the “No Go” decision at a high cash tag. Although sustainable production of ineffective water is generally acknowledged as the limiting factor, little has been devoted to understanding the role of IAA as pertaining to reservoir-specific structural style and the hydrodynamics of CBM described in the present work.

In the Qinshui Basin in China, a large number of CBM wells face low gas production during the development of the reservoirs linked to high water production, and many studies analyzed the conditions, but few conducted a comprehensive analysis to determine the nature of the causes on well basis. A study in the Shizhuangnan block in the south Qinshui Basin was set as an example to analyze the key factors causing high water production of five CBM wells to conclude that strong structural influence, as the catchment area formed in the depression zone in the north section of the block increase the risk of high-water production since the coals seam easily communicated with the overlying aquifers [24]. These conclusions relate well to the principle of sustainable groundwater yield and the source causes set for IAA. A different approach to implicitly study the implications of IAA on CBM production was researched based on the hydrochemical closed index (HCI), a new parameter based on the ion composition of the groundwater, which was used to the quantitative discrimination and description of superimposed CBM system as based on the determination of the groundwater environments [25]. The research concluded that the hydrodynamics of the upper CBM systems are stronger with lower HCI value and thus susceptible to shallow groundwater interference, in other words, the conditions of sustainable groundwater yield from IAA during the production of CBM. Further numerical simulations showed that the upper CBM system limits the production of the lower CBM system, suggesting that IAA plays an active role triggered in this case by cross-formational flow.

Neglecting the implications of IAA on gas desorption during the exploratory stages may lead to a misleading decision-making process. On one side, decisions based on high methane content from cores would result in too optimistic prospects with high probed reserves but low recovery rates. The ones based on pilot testing, which show high water production with no adequate assessment of IAA, on the other side, may lead to overlooking potential sweet spots and premature ruling out of the prospects. Recognizing the role of IAA may at least support holding the pilot testing until further evidence is collected regarding recharge conditions, potential of biogenic gas generation, and methane saturation.

These key exploration issues have been preliminary addressed in this work by comparing the previous results of IAA assessments for the US and CLS, as reported by Rivera [9] and ANH-UPTC [6]. On one side, open, symmetrical synclines with both outcropping flanks are more likely to develop a U-Tube with open ends like hydraulic setting with contributions from both original recharge and captured discharge from neighbor prolific aquifers or crossformational flow, e.g., US. Therefore, an extended dewatering period to remove the ineffective water is expected, with a consequent delay in the production of methane. The relatively high concentrations of methane measured in the coals from core holes and high-water–low-methane presence inside the underground mine works indicate that sustainable groundwater yield persists, so the reservoir is yet to reach the critical desorption pressure to release the methane.

Research in the Tiefa coalfield and the Qinshui basin in China informs that commercial desorption of CBM reservoirs would occur with a pressure drop that is at least 1 MPa or greater [26, 27]. Merging this cutoff with the results in the US, it could be implied that such a level of depressurization would be reached only with dewatering at high rates, e.g., $\geq$500 m^3/day, after 20 years of dewatering [9].

Closed, asymmetrical synclines with only one outcropping flank and closed-end flanks due to faults, pinching, or thinning in thickness, on the other side, behave as a U-Tube with a closed-end like a hydraulic setting observed in the south sector of the CLS. The reservoir there would be subject to limited original recharge and capture of discharge to attenuate; otherwise, eliminate the implications of IAA. Dry coal seams with gas release through the vented flank that contrast with methane entrapment in the nonvented one would be expected. Therefore, the reservoir would be close to or at the critical desorption pressure, and the production of methane would be anticipated in the short term. The presence of methane and low-cut water in underground mining works in the west flank (vented end) of the CLS contrasting with high water–low gas shows in the eastern one (nonvented) support that presence of IAA conditions is negligible in the west flank of CLS as assessed via numerical simulations (Figure 9).

In symmetrical structures with both open ends, pilot testing would start at the axis of the structure where low groundwater potential is expexted. If IAA conditions occur, the production of methane would be negligible to nil, an indication that reservoir depressurization would extend beyond commercial feasibility. In asymmetrical structures with at least one closed flank, attractive pilot and production targets would be expected at the axis of the structure progressing upgradient along the closed flank where higher methane saturation is expexted and the production of ineffective water would be unsustainable to trigger reservoir depletion and methane desorption in the short term.

6. Conclusions

IAA conditions, or sustainable water yield, inhibit methane desorption and become the main challenge for CBM development. Under the IAA type of flow, reservoir depressurization may require extended dewatering prior to reach the critical desorption pressure while delaying the first production of CBM to potentially make it economically unfeasible.

IAA is driven by structural style, methane saturation, generation of secondary biogenic gas, and recharge, and its assessment relies on data availability from lab pilot testing, which is quite often scarce, and numerical simulation. Single-phase numerical flow assessments carried out to evaluate IAA conditions in structurally challenging synclines suggest that open and symmetric folds are likely to develop U-Tube with open ends like hydraulic settings with sustainable groundwater yield to drastically impair the production of methane. Asymmetrical synclines with closed flanks—fault truncated—on the other hand, may develop conditions of restricted water circulation, limited recharge, and efficient reservoir dewatering ideal conditions to reach the critical desorption pressure while enabling methane desorption in the short time.

The results of a numerical simulation to assess the removal of ineffective water in the selected field analogs suggest that the US is severely impacted by IAA conditions and is yet to reach the critical desorption pressure; therefore, the production of methane would likely face severe hydrogeological challenges before reaching to the commercial stage. On the contrary, dewatering assessmen for the CLS suggests the reservoir is at or very close to the stage of effective water production; therefore, it would be considered ready for production of methane. From the arguments related to the IAA conditions presented here, the CLS would be the best feasible option to start a CBM pilot project in Colombia.

Despite the numerical recognition of the IAA and its potential implications for methane desorption, validation of the hydrogeological challenge is yet to be field addressed forward to its final confirmation. The validation is to clear the outstanding issues regarding methane saturation, recharge, and generation of biogenic gas as final steps toward pilot testing and the declaration of commercial production of CBM resources in structurally simmilar reservoirs worldwide.

Data Availability

No underlying data were collected or produced in this study. Previously reported modeling data were used to support this study and are available at https://doi.org/10.1016/j.coal.2019.03.018 and internal institutional government reports. These prior studies are cited at relevant places within the text as references ANH-UPTC [6] and Rivera [9].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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