

Article

Modeling and Forecasting of Coal Bed Methane Reservoir from Raniganj Coalfield, India

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Abstract: Demand for a cleaner source of energy is increasing in India. In the search for alternate energy sources, coal bed methane gas receives considerable attention for its potential as a good energy source. During the coalification process, methane gas is captured in the coal seams and later released during coal mining operations. Coal bed methane separation is crucial for both economic benefit and methane emission reduction. The methane production from seams is an efficient way to reduce greenhouse emissions and provide a safe mining operation environment. In India, the production of coal bed methane on a commercial scale has been recently observed. In the present paper, an attempt is made to understand and establish a 3-D excavation of coal bed methane from reservoir simulation (COMET³) for Gondwana coal seams in the Sitarampur block of the Raniganj coalfield in India. The simulation study was carried out for a period of 25 years for the recovery of methane from the reservoir. It is observed from the simulation study that 372 million cubic meters CO₂ equivalent greenhouse gas emissions can be prevented by the extraction of methane with space and time. The fracture gas concentration increases with time, and it is observed that fractures are fully saturated with gas in 3000 days.

Keywords: coal bed methane; reservoir modeling; productivity prediction; COMET³; Gondwana; bituminous coal

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1. Introduction:

While India is looking for a cleaner energy source, it is important to identify the potential of coal bed methane (CBM). CBM plays a vital role in the country's economic development and makes the future mining environment safer without substantially adding to the atmospheric greenhouse gas emission levels. During the coalification process, methane is the pure form of methane trapped within coal seams and released during mining operations [1–3]. The depth of the coal seam significantly affects coal quality and gas content [4,5]. Most of the methane emission comes into the atmosphere from the underground coal mining activity [5–7]. Most coal mine accidents have resulted from methane gas emissions, which turns out to be an explosive gas; thus, it is necessary to degasify the coal seam for mine safety and the safety of mine workers [8–11]. The process of recovering methane gas directly from the surface, or by boreholes from the coal seam before mining activity, is commonly known as coal bed methane or virgin coal bed methane [12–14].

Methane concentration in virgin coal bed methane (VCBM) is generally very high (>90%), which makes it eventually an additional source for natural gas supplies [15–23]. Methane gas, released during the mining activity and therefore released into the atmosphere by the ventilation system, is known as ventilation air methane [24]. The methane concentration present in ventilation air methane (VAM) is significantly less, so it is not suitable

for industrial utilization purposes [25]. However, currently developed oxidation technologies can generate electricity using thermal energy recovery by VAM as a fuel [26–29]. It contributes around 60–70% of total methane emissions into the atmosphere [30,31]. With coal mine methane (CMM) in underground mining of coal, methane is also recovered along with coal, so it is necessary to reduce methane concentration in the mine area for its proper workings, safety and efficient utilization [32,33]. Extraction of CMM is necessary for highly gassy seams and is essential before mining, and this captured gas from coal seams is a beneficial source of energy [34–38]. The world resource of CBM is assessed as around $1.4 \times 10^{14} \text{ m}^3$, which makes it a valuable conventional resource [39]. The coal basins present in India are divided into four categories according to their area, geological age, coal quality, gas resource and depth of coal occurrence, as shown in Figure 1 [40]. Raniganj coalfield is one of the largest coalfields, and the coal seams present in this area are thick and carry high-rank bituminous coal with the considerable resource of coal bed methane [15–22]. One virgin coal block from Sitarampur located in the Burdwan district of West Bengal was being explored by Mineral Development and Trading Corporation Limited, Kolkata. It may not be possible to mine out these coal seams without pre-mining degasification.

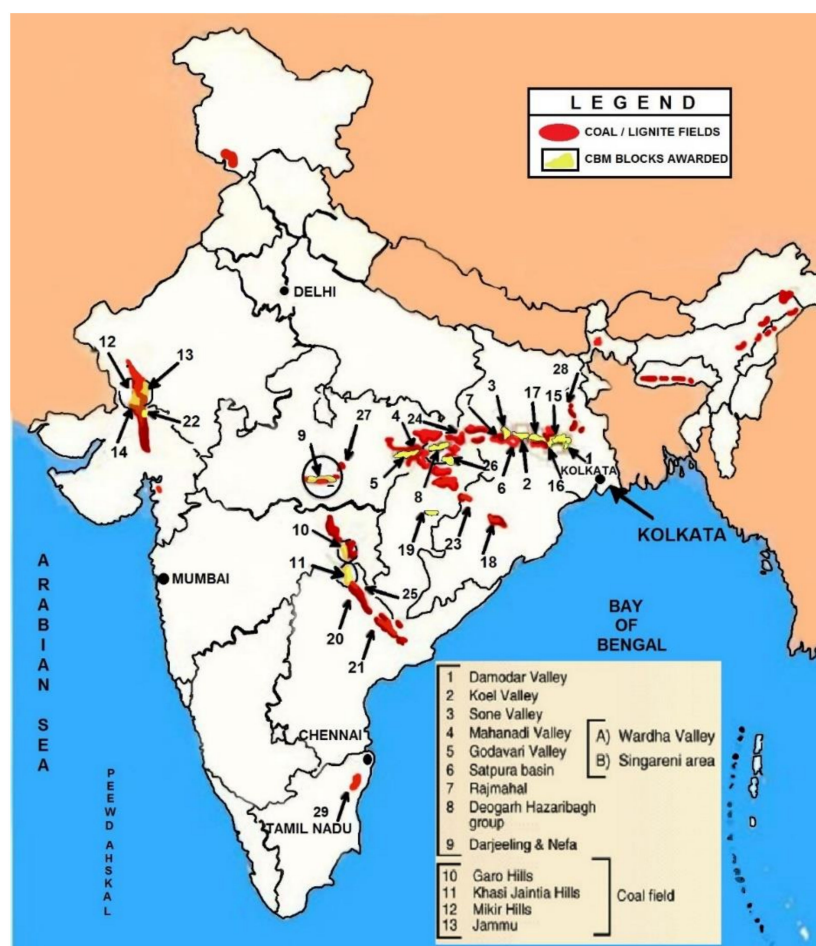


Figure 1. Classification of coalfields based on CBM potential, India.

In this present investigation, one virgin highly gassy coal block from Sitarampur located in the Burdwan district of West Bengal was chosen for methane extraction. A simulation study was based on vertical wells degasification of the coal seams. Reservoir simulation was implemented to assess fracture gas saturation, matrix methane concentration and water production with time. The present numerical study's finding is based on the fact that coal bed methane exploration and exploitation activity in India is still in the initial stages.

2. Methodology

COMET³ is one of the best, most stable, calibrated and known reservoir simulators; it is extensively used for three-dimensional (3D), two-phase, single or dual-porosity simulation for modeling gas and water production from coal seams and a single permeability model capable of modeling desorption controlled reservoirs. Therefore, it was used to simulate the production profile for two coal seams present in the block. COMET³ is well understood, based on the finite-difference method and specifically designed for modeling the flow of fluid in coal seams.

2.1. Numerical Modeling of CBM Process

In general, coal bed methane reservoir refers to a dual-porosity and naturally fractured reservoir. Dual-porosity is divided into two parts; the primary porosity is dominated by deposition condition and coalification, whereas the secondary porosity is dominated by water solution, natural fracturing and jointing. A large amount of gas formed during the maturation of coal is stored in a coal matrix (95–98%) by the adsorption process. Some gas is also present in the cleats system in free or dissolved form. The cleat system provides media for fluid flow in the coal seam formed during the regional burial and maturation [41–45]. The fracture zones affect the economic gas production of a reservoir [46–48]. When there is pressure reduction through dewatering, gas desorption starts from the matrix and diffuses to the cleat network system. This diffuse gas flows into the cleat system, produced by convective flow [49]. Many reservoir phenomena must be implicit before modeling coal beds for CBM recovery [50,51]. The change in permeability affects the gas flow rate, dual-porosity, heterogeneity and anisotropy in coals, and gas flow mechanism in the reservoir, including transport of gases by diffusion and flow in the cleats system [52–57]. The volume of gas involved or adsorbed on coal surface can be estimated by Langmuir's isotherm.

2.2. Controlling Equations Used in Modeling

The basic mass conservation equations used for dual-porosity and the single permeability system are shown, respectively, in Equations (1) and (2).

For Conservation of Gas:

$$\nabla \cdot [b_g M_g (\nabla p + \gamma \Delta Z) + R_{sw} b_w M_w (\nabla p_w + \gamma_w \nabla Z)]_f + q_w + q_g = \frac{d}{dt} (\phi b_g S_g + R_{sw} \phi b_w S_w)_f \quad (1)$$

For Conservation of Water:

$$\nabla \cdot [b_w M_w (\nabla p_w + \gamma_w \Delta Z)]_f + q_w = \frac{d}{dt} (\phi b_w S_w)_f \quad (2)$$

$$P_{cgw} = P_g - P_w \quad (3)$$

$$S_g + S_w = 1 \quad (4)$$

$$q_m = \frac{V_m}{\tau} [C - C(P)] \quad (5)$$

where $\nabla \cdot$ is divergence operator, ∇ is gradient operator, M_g is gas phase mobility, M_w is water phase mobility, R_{sw} is gas solubility in water, b_g is gas factor, b_w is water shrinkage factor, p_w is water pressure, γ_g is gas gradient, γ_w is water gradient, Z is elevation, q_w is water flow rate, q_g is gas flow rate, ϕ is effective fracture porosity, S_g is gas saturation, S_w is water saturation, P_{cgw} is capillary pressure, P_g and P_w are related by capillary pressure, q_m is described mathematically by Fick's first law of diffusion, C is the average matrix gas concentration, τ is the sorption time defined by $\tau = 1/D\sigma$, where D is the diffusion coefficient and σ is the Warren and Root shape factor, and V_m is the bulk volume of a matrix element.

2.3. The Assumptions Used for the Development of the Model

- (a) There is no thermal change occurring during the gas production from the reservoir.
- (b) The reservoir contains two phases: methane and water.
- (c) Methane is not soluble in water.
- (d) The flow of fluid inside the cleats or fracture system is assumed as laminar flow according to Darcy's law [58] and flow measurement is done through relative permeability.
- (e) All matrix blocks are homogeneous; however, the matrix block is in equilibrium with the fracture system.
- (f) The thickness of the seam is alleged to be uniform.
- (g) Pseudo steady-state flow condition existed in between the matrix and fractures.

The above assumptions are the classic Warren and Root assumptions [59] and assume that the concentration throughout each matrix element is declining at the same rate.

2.4. Model Development

In numerical modeling and simulation practices, coal seams are represented as rectangular or cylindrical shape geometries. Cylindrical geometry was used to simulate the production profile of the present reservoir. In this model, a dual-porosity, single permeability, two phases (water and gas), single-component sorption model was selected to simulate both gas and water production from the reservoir and estimate gas recovery.

This model applied to a $569.06 \times 569.06 \times 14.93$ m block of the coal seam. For the production of methane, the well diameter chosen was 0.1079 m. The simulation purpose model was distributed into 15 grid cells of 40.65 m in both the x and y direction and two grids of 14.93 m in z-direction in Figure 2. The various reservoir parameters which are inputs for the present study model are fracture properties, matrix properties, gas and water properties, basic reservoir properties such as reservoir temperature, reservoir pressure, coal seam thickness, sorption time of methane, and gas and water relative permeability curves. One vertical producer well is located in the centre of the coal matrix, and production results are used to simulate the gas production conditions in the field. The reservoir parameters in the present investigation are reported in Table 1.

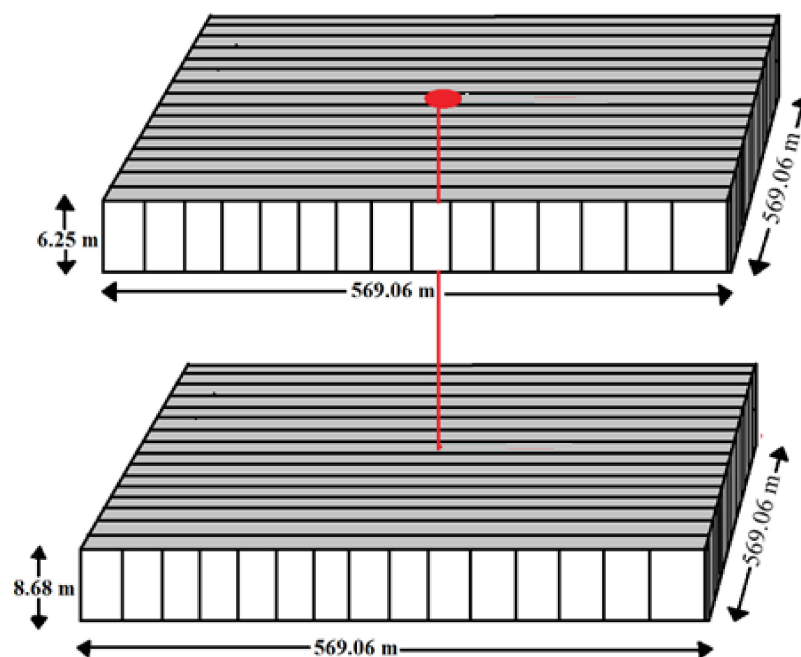


Figure 2. Grid view of block used for reservoir simulation.

Table 1. Input parameters used for simulation study.

Parameter	Value	
	Seam-I	Seam-II
Reservoir temperature (°C)	61.72	64.94
Depth (m)	657.98	755
Permeability (mD)	1.84	1.25
Density of coal (kg/m ³)	1280	1320
Cleat porosity (%)	0.50	0.50
Thickness (m)	6.25	8.68
Sorption time (days)	1.42	0.21
Initial matrix content (m ³ /t)	7.12	7.67
Fracture spacing (m)	2.54×10^{-3}	2.54×10^{-3}
Langmuir volume for methane (m ³ /t)	17.98	21.82
Langmuir pressure for methane (atm)	44.76	40.51

In this present study, a mathematical model was used to estimate the deviations in fracture gas saturation, water production and matrix methane concentration. In the end, the numerical values were noted for the highest saturation point at different time intervals. Methane and water production rates have been systematized for a specific time spell.

3. Results and Discussions

Pressure and concentration gradient plays an imperative role in gas production from the reservoir. Since lower coal seams are the primary target for CBM production, most of the coal bed methane reservoirs are considered water-saturated. It is necessary to depressurize the reservoir by a dewatering process for improving gas production. Dewatering augments the gas flow through the cleats system towards the production well, and thus, the productivity of the well gets advances.

3.1. Matrix Methane Concentration

Methane is found in a coal bed as adsorbed and this adsorbed form constitutes 90% of the total amount of gas. It is the gas generated during the formation process and stored in the pores within coal seams. The transport of gas in coal seams is believed to occur in three distinct stages. The first step involves desorption of gas from the micro-pores' walls due to continuous pressure decline. The gas diffuses through the interconnected micro-pores from the region of higher concentration in the cleat system towards lower concentration. The gas is then transported through the coal seam cleat network under Darcy flow conditions.

Methane is produced through a vertical well situated close to the centre of the field. Figure 3a–e show the variations of methane concentration along the coal seams with time, ranging from 1000 days to 9000 days. It is apparent that the concentration of methane is high in the coal seams before production and reduced continuously after the production started. The gas production rate incessantly increased with time and obtained its peak value of 2713.2 m³/d in 1948 days and subsequently started to decrease. The coal quickly desorbed approximately 1.2 Mm³ of methane in 730 days while it desorbed methane at a rate of 2308 m³/d in 4000 days and with the rate of approx. 1504 m³/d in 8000 days. With the continuous gas production process, the rate of desorption declines, and it was found to be at the rate of 1345.2 m³/d in 9125 days from the beginning of the process.

The information came from cumulative methane production; it has been observed that during the initial stage, the methane production rate is low for specific periods of time and achieves a constant rate until 70 days (Figure 4). The wells produce 9.51 Mm³ in 4000 days and 17.01 Mm³ in 8000 days. The well produces 13,783.70 m³ in 70 days, and after that, as

the production goes on, the cumulative methane produced is up to 2.95 Mm³ and 6.56 Mm³ in 1450 days and 2800 days, respectively. The well will produce around 18.6 Mm³ in a time duration of 9125 days.

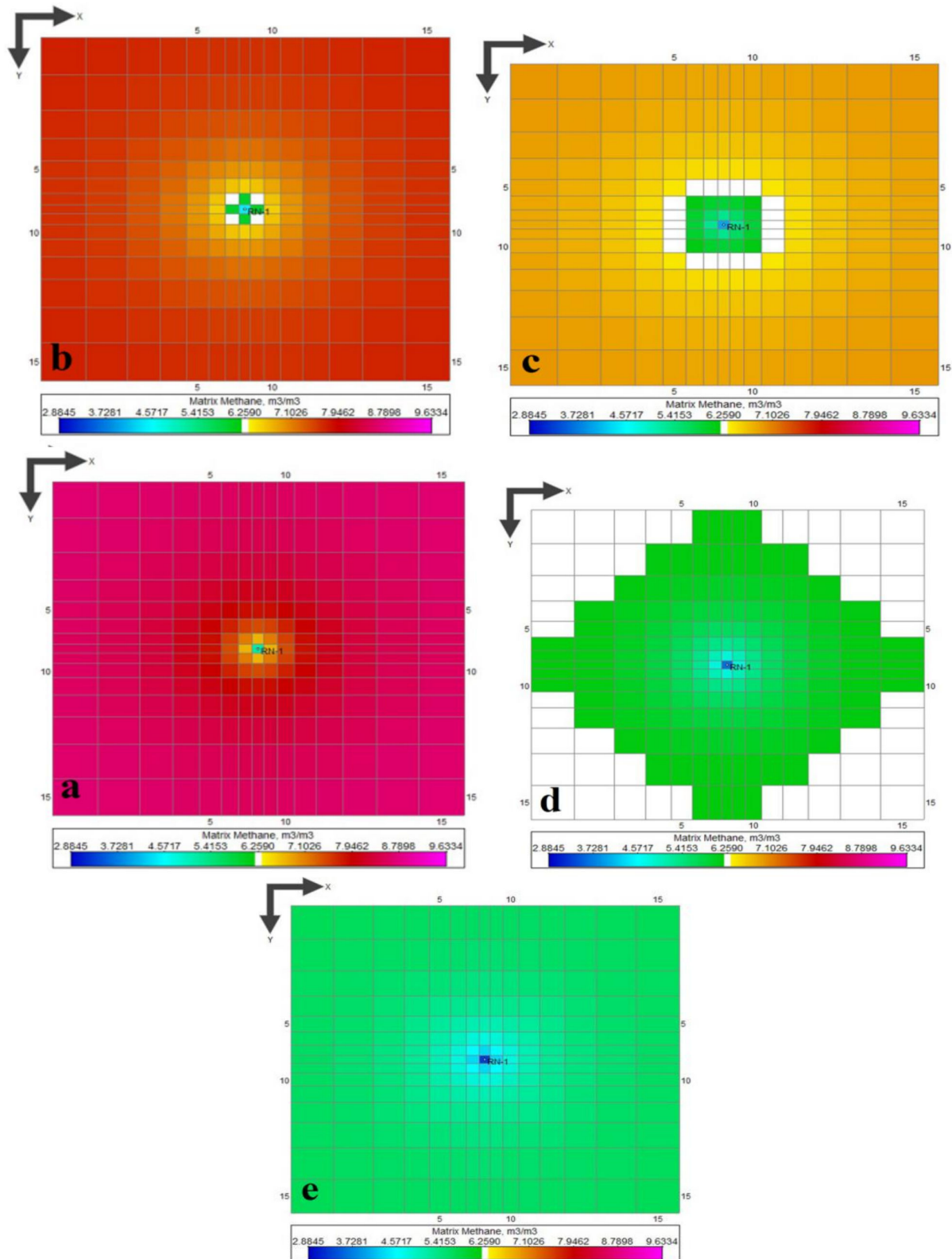


Figure 3. (a–e). Matrix methane concentration in the area over a period of 1000 days, 3000 days, 5000 days, 7000 days and 9000 days, respectively.

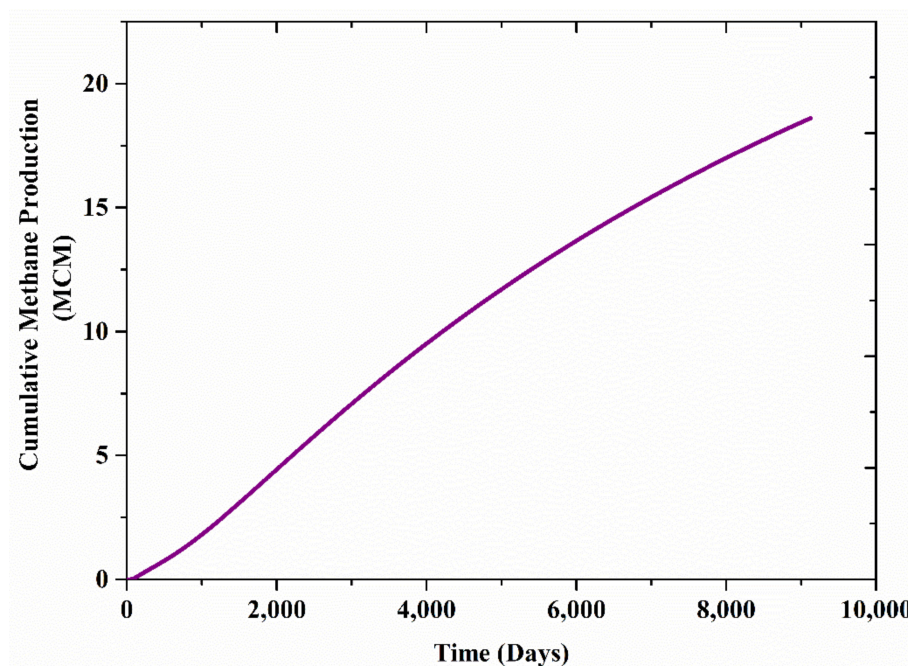


Figure 4. Cumulative methane production vs. time.

3.2. Fracture Gas Saturation

Permeability is known to be the primary factor affecting methane and water recovery rates from coal wells. Because the permeability of coals is controlled by fractures in the coal, it can vary significantly as a function of pressure and gas concentration and can be highly variable on a well to well basis. The permeability of coal can vary by several orders of magnitude with a pressure change of 3500 kPa. Also, coal permeability is believed to increase as the gas is desorbed from matrix structure associated with desorption of gas.

The change in fracture gas saturation with time and space for the field is clearly seen in Figure 5a–e. At the beginning of production, dewatering reduces the reservoir pressure so that the gas can be easily diffused from micro-pores to the fracture system. Dewatering improves the saturation level of fracture gas, which enhances gas production. The water production helps to raise the % saturation of coal with time (as shown in Figure 5b). At the beginning of production, higher fracture saturation is experienced around the production well. An attempt has been made by taking advantage of grid graphs to approximate the volume of methane produced with space and time. The grid plots noticeably depict the distribution of gas. It helps to visualize the gas concentration changes during the gas recovery process from the coal matrix for a period of 9125 days.

3.3. Water Production

Water production is one of the initial steps for CBM extraction from a reservoir. In general, CBM reservoirs are considered as water-saturated, and water develops the hydrostatic pressure to hold gas in coal seams. The depressurizing is done by dewatering so that the reservoir pressure comes below the saturation pressure of methane, and gas production starts from the CBM well. So, the water production rate becomes a significant factor that affects the recovery of methane from CBM reservoirs. Figure 6a–e show variations of desorption pressure with water production and time, ranging from 1 day to 6939 days. It is evident that the water production rate is initially high, and slowly it is reduced. The water production rate incessantly declined with time and attained its peak value of 50.7 m³/d at the beginning of the first month. The reservoir quickly dewatered approximately 3729.5 m³ of water in 90 days while it released a total of 22,117.3 m³ in 6939 days.

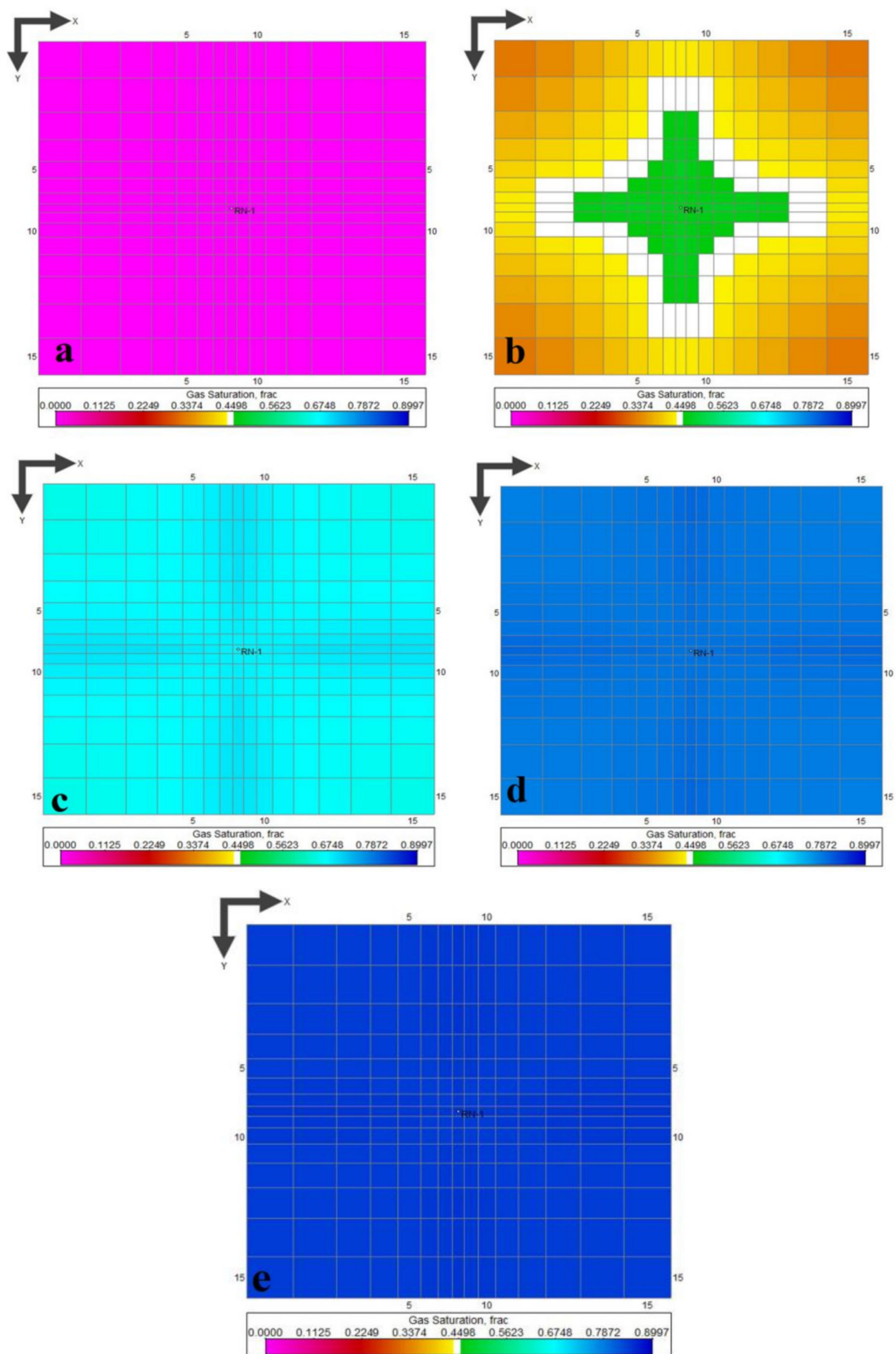


Figure 5. (a–e). Fracture gas saturation in the area over a period of 0 days, 1000 days, 2000 days, 3000 days and 4000 days, respectively.

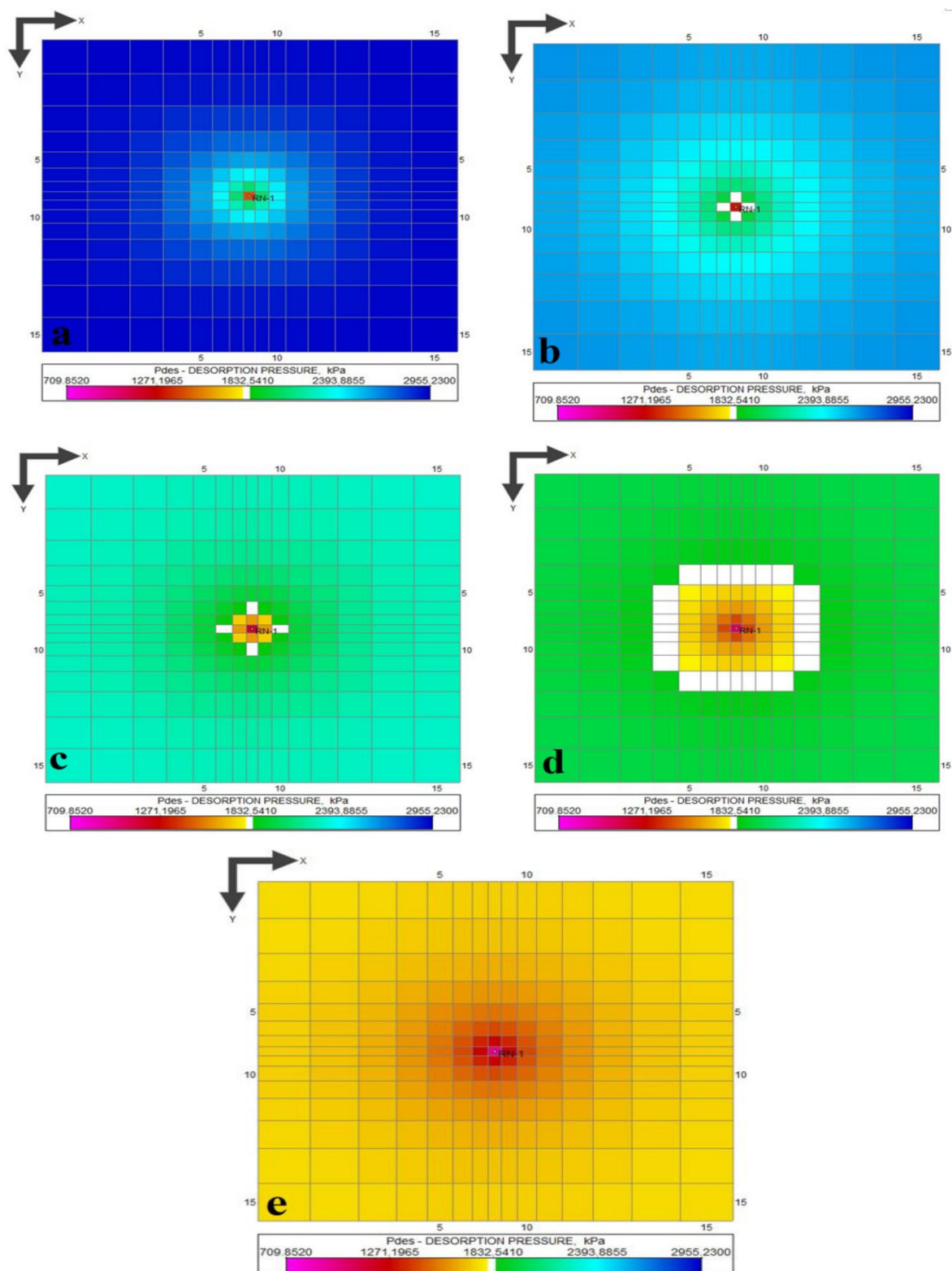


Figure 6. (a–e). Effect of water production on desorption pressure the area over a period of 1000 days, 3000 days, 5000 days, 7000 days and 9000 days, respectively.

The plots of cumulative water and water production rate from the vertical well designated show that the rate of water production is slightly high for starting days. It is observed in the field that water production increases at an incline speed constantly monitored up

to 60 days, and after that, it started declining for the remaining duration from 9125 days (Figures 7 and 8).

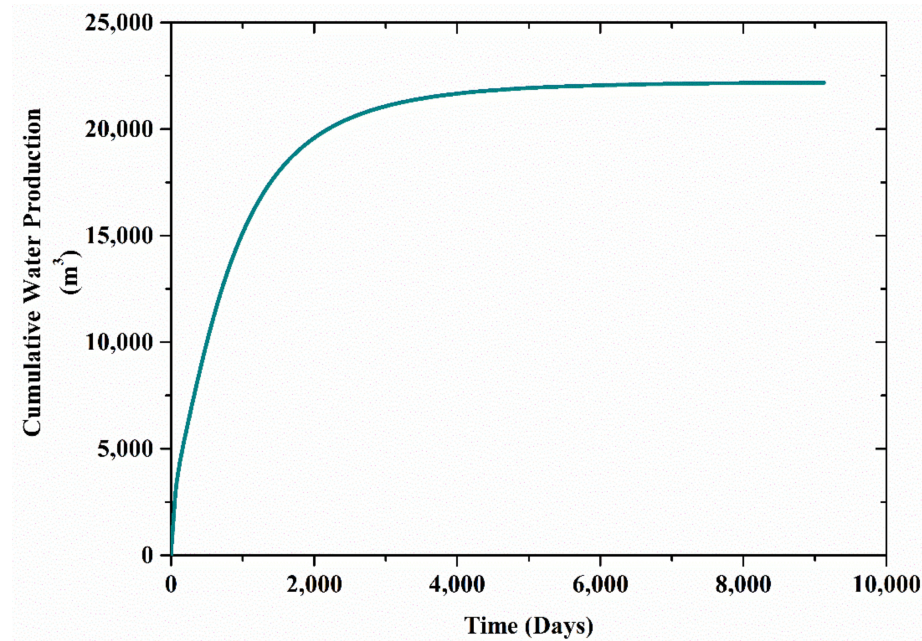


Figure 7. Cumulative water production vs. time.

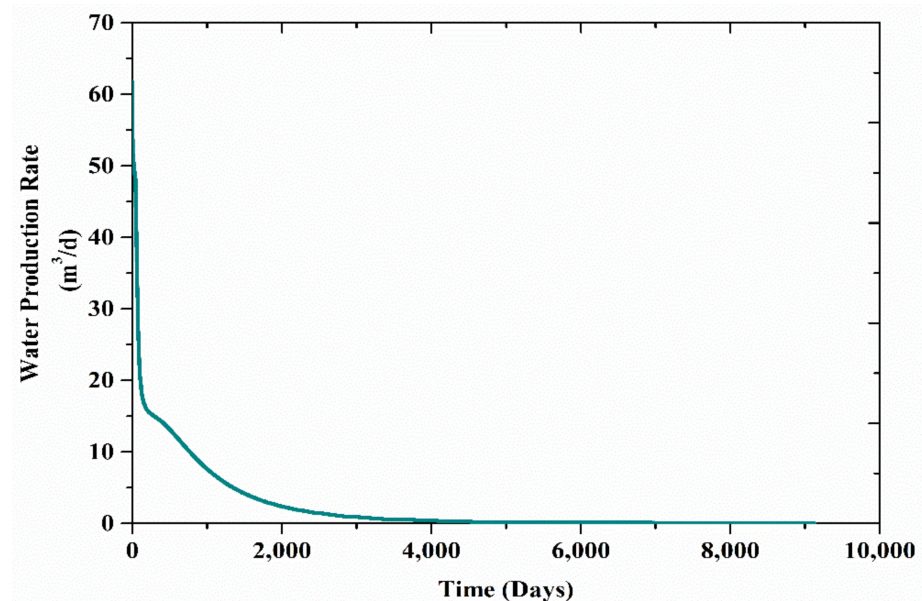


Figure 8. Water production rate vs. time.

3.4. Scope for Future

Currently, there are many comprehensive policies available which support the resource estimation and analysis at various active sites in India. The salient features of new CBM policy are as follows: (i) coordination between multiple agencies, (ii) simultaneous mining of coal and CBM, (iii) use of CBM from existing coal mines, and (iv) pricing of CBM. The above policy might be helpful to attract new companies for extraction of valuables from potential sites.

The present study illustrates that simulation study on an area provides precise information which could be used as foundations for actual resource estimation and analysis. Reservoir production data will be very helpful to provide detailed information about

various source rock properties (coal), methane production capacity, methane production rate and the feasibility of production followed by economic data. Modifying models based on production data from coal bed methane reservoirs helps to estimate carbon storage sites. Economic analysis with details can be involved in judging the commercial value of ECBM wells.

4. Conclusions

The Sitarampur block of the Raniganj coalfield is bountiful in gas content with good permeability. The present study illustrates that a tremendous amount of gas recovery can be possible from these coal seams with less water production. The extraction of methane also improves the safety of coal mines. The recovery of methane from such a highly gassy seam helps protect our atmosphere from global warming and provides an alternative energy source. This study also approximates the technical feasibility of vertical wells for degasification of coal seams present in the block.

The underground coal mines are the main source of methane emissions in India due to their mining activity. The extraction of methane before mining operations ameliorates coal mine workers' safety along with coal's economic production. The coal seams present in the Sitarampur block are highly gassy in nature. The recovery of methane from such highly gassy seams helps protect our atmosphere from global warming. Methane is a valuable fuel with good calorific value which is easily recovered from underground coal mines. The simulation study shows that lower coal seams are more suitable for coal bed methane recovery. The present study illustrates that a tremendous amount of gas recovery can be possible from these coal seams with less water production. This study also estimates the technical feasibility of a vertical well for the degasification of the coal seam.

- (a) This study illustrates that the chosen coal seams of the Sitarampur block can produce an expected 18.60 MCM of methane and 22,117.30 m³ of water over a period of 9125 days.
- (b) These coals desorbed methane slowly and attain a peak value of the gas production rate of 2713.2 m³/d in 1948 days, which shows that the gas desorption rate is low in both coal seams.
- (c) The fracture gas concentration increases with time, and it is observed that fractures are fully saturated with gas in 3000 days. The gas concentration is high near the production well due to a quick diffusion rate of gas and water production.
- (d) This study concludes that approximately 70% of gas recovery can be achieved by this method over a period of 9125 days.
- (e) A simulation study demonstrates that the extraction of methane can prevent 372 MCM equivalent CO₂ emissions.
- (f) The desorption study of coal samples shows that the gas content of coal samples increases with depth.

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List of Abbreviation

CBM	Coal Bed Methane
VCBM	Virgin Coal Bed Methane
VAM	Ventilation Air Methane
CMM	Coal Mine Methane
ECBM	Enhanced Coal Bed Methane

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