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Management of Cross-Border Hydrocarbon Migration in Field Development Plans, a Case Study of Shared Oil and Gas Fields

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Abstract

It is the natural right of each country to exploit its underground resources. Production and development of a shared hydrocarbon formations can be performed independently, nevertheless any production or pressure change can have irreversible effect on the whole reservoir. Iran is one of the unique countries in the world, having shared oil and gas fields with at least six neighborhood countries. Some of these fields have been developed earlier and some are just under development. The purpose of this paper is to investigate development plans that can maximize the productivity of one party from a shared field. Fluid migration crossing border is simulated based on real field data with Eclipse software. Different scenarios are run to find different cross-border fluid encroachment. Finally, two sets of factors are recognized: development parameters and the intact reservoir properties. Application of these two types of parameters enables any country to manage the border fluid and to compensate the possible arrearage of production from shared reservoirs. Findings of this study are applied to investigate the development plan of a giant gas field named PASO. Some cross-border gas migration has already happened but managing the fluid in the border can compensate further lose of underground resources.

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1. Introduction

Development of shared reservoirs is a challenging task especially in a competitive environment between two neighborhood countries to drain more of the interconnected reserve. Equal production-rate agreement from shared fields may not be sensible because it is the right of each country to produce their own resources with any scenario based on their policy. Equal or proportional cumulative production is technically not acceptable because based on field experiences determination of the accurate reservoir volume has some uncertainty that can be existed even after several years of development. Even if the share of each party from a reservoir is known, each point of the reservoir has its own static and dynamic properties. Take porosity, oil saturation, permeability distribution and aquifer or gas cap status as examples. These differences may have influence on regional potential of one shared reservoir.

Iran is one of the unique countries having 28 proven shared reservoirs including 18 oil fields, 4 gas fields and 6 oil and gas fields with 6 neighboring countries. Among all common fields 15 of them are offshore and 13 onshore, 12 of these basins are common with Iraq, 7 are in the border with United Arab Emirate (UAE), 4 with Saudi Arabia, 2 fields common with Qatar, and one with each Oman, Kuwait and Turkmenistan neighbors. The probable reservoirs in Caspian Sea are excluded. The production rate of Iran in all borders is less than neighborhood countries. **Table 1** is the daily production rate of Iran with some neighborhood countries [5]. This could be logical depends on corresponding volume share of the reservoir, but the permanent effect of draining reservoir on neighborhood country's share should be scrutinized.

The biggest shared oil reserves of Iran are located in border with Iraq with more than 14 billion barrels of recoverable oil. Iraq, after overturning Saddam, severely needs to escalate oil export. This country recently conceded 70 exploration blocks and 65 oil fields to international oil companies. Well-known oil companies from England, Russia, France, China, Norway and Malaysia won the tenders and committed to invest 8 billion dollars in 2012 year and 20 billion dollars in the following three years. The purpose of Iraq is to increase their daily production from current daily rate of 2.5 million to 6 million in four years and 12 million in 6 years [4]. Rapid investment in Iraq soil is targeting towards daily production rate of 2,850,00 barrels from common reservoirs with Iran till 2017. While the production in each side of the reservoir can reduce the performance of the other side, with international strains and sanctions the possibility for Iran to compete with Iraq rate of development is hardly achievable.

Iran has also 28 trillion cubic meters gas reserve and 50 percent of them are in shared reservoirs [5]. The importance of all is a giant gas field elongated from Iran to Qatar and named South Pars-North Dom in corresponding countries. Iran has the estimated share of 14 trillion cubic meter of gas and 17 billion barrels of gas condensate. As shown in **Table 1** the production of Iran from the gas zone of this share reservoir is about half of its neighbor and the production from its oil zone is zero while Qatar is producing 450,000 barrels per day.

Looking to this numbers and the amount of obtainable profit by each country can encourage any party to set a priority to develop these fields. Although the best

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development plan is the integrative reservoir management of shared reservoir with cooperation and sharing data among neighboring countries but this fact is rarely achievable due to economic issues and political conflicts [2]. International tensions, wars and regional divergences lead the neighboring countries to exploit their share of the reservoir independently. In some fields the neighboring countries has surpassed Iran, but Iran is ahead of neighbors in some others. However producing from common oil and gas fields has consequences for neighborhood country.

Producing from one section of a shared reservoir can have two influences on the reservoir, first the pressure declines due to draining some fluid volume of a reservoir. This pressure drop may be compensated with available aquifer or gas cap drive mechanisms, but in any case some hydrocarbon fluid is swept. Second is the cross-border migration of hydrocarbon fluid from underground boundary of one country to the neighbor's. In other words the fluid belonging to one country is moved to the neighboring country permanently. In this paper a sector modeling of different shared reservoirs are presented and pressure drop and cross border hydrocarbon fluid movement are scrutinized. Then the findings are applied to investigate the undergoing developments in one gas field.

2. Research Methodology

In petroleum science the movement of fluid in porous media is correlated by Henry Darcy in the year 1856 [1]. This relation for one dimensional fluid simplified as follow:

$$q = -c\frac{kA}{\mu}\times\frac{dP}{dx} \qquad (1)$$

Where q، k، A، μ، P and x are liquid rate, rock permeability, rock cross section, fluid viscosity, pressure and length of rock respectively. And the constant c is a unit conversion coefficient. This relation shows when there is pressure difference between two points, depends on rock and fluid properties, fluid displacement occurs. In a well producing from one extended reservoir layer the fluid movement is radial. With application of mass balance in radial differential system and applying mass and momentum balance [1] and using Darcy's law, another important correlation is derived which is called diffusivity equation. Diffusivity equation is a second order partial differential equation as a function of place and time. Diffusivity equation is written for an oil or gas reservoir as following:

$$\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} = \frac{1}{\eta}\frac{\partial\psi}{\partial t} \qquad (2)$$

Where ψ is the fluid potential and η is diffusivity coefficient and defined as:

$$\eta = \frac{0.000264k}{\phi\mu c_t} \qquad (3)$$

Where ϕ and c_t are rock porosity and fluid compressibility respectively. The value of diffusivity coefficient implies the movement of pressure drop wave. The travelling time of this wave propagation in any radius of r_e of homogenous reservoir is calculated with

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$t = \frac{r_e}{\eta}$ correlation. For any production rate, one pressure drop is formed and the corresponding wave will move through the whole reservoir. The direction of fluid migration is all determined by superposition of pressure waves. When a wave touches the border, depends on its strength, it starts to pull the fluid from other side of the border. Whatever the amount of η in one side of the reservoir is more (i.e. more permeability, less porosity, viscosity and compressibility), its production is more and fluid of the border moves towards this section of the reservoir. In reality in a reservoir, fluid properties like viscosity and compressibility are constant but permeability and porosity depends on depositional environment could be varied in different spots. In this paper, the influence of different factors on movement of pressure drop wave and consequently fluid movement direction through shared reservoirs is investigated. Due to exorbitant cost of drilling and production investment in shared reservoirs and also the value of time to manage reservoir fluid in the border, this study is quite helpful and necessary.

To construct proper oil and gas models, commercial Eclipse software is deployed with real reservoirs data. The basic model has homogeneous static and dynamic data without inclination. Two regions of the reservoir have been considered to apply Tracer command of Eclipse in order to track the crossing border fluid. Ten wells in each side of the country with equal distance from the border are designed which have the same production constraints.

3. Cross-border fluid displacement

The dimensions, rock and fluid properties of the basic models are collected in Table 2 for an oil model and Table 3 for a gas model. Fluid characteristic is the same all along the reservoir models. Figure 1 is the basic model divided between two countries (each color is in the territory of one country) and 10 wells is considered in each side of the border with the same production constraints. To indentify the parameters pro and against cross-border fluid, they are divided into two major categories: first are those in hand of Production Companies which are related to development strategies and second are reservoir characteristics that are intrinsic and cannot be changed. Importance of these two considerations in maximizing the recovery of a shared reservoir is discussed in the following.

3.1Field Development Techniques

3.1.1 Production Overtaking

Considering diffusivity equation and Darcy’s law, it is obvious that production time is an obvious factor in amount and direction of fluid (oil and gas) migration across underground border. To determine these qualitative and quantitative parameters, in the basic model the production start-up of one region of the reservoir is set to be three years earlier. In **Figure 2 and Figure 3** the cumulative oil and gas displacements through border in oil and gas models are shown separately. As shown in the oil model, the overtaken region pulls 1.1 percent of total reserve to its own region during first 8 years of production. In the gas model, since pressure wave movement is faster (higher compressibility), the effect of overtaken country is detected in the first 3 years of

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production. Afterwards there will be a pressure drop balance in both sides of the border and no fluid migration will happen across the border and only the remaining reservoir potential is shared between two parties.

3.1.2 Well distance from border

Running the model for symmetrical rows of wells shows similar circular movement of pressure drop in both sides of the boundary. Naturally, these pressure waves reach the border at the same time and counteract with each other. It results in no migration of fluid crossing the border. This is the ideal development plan in a shared reservoir when no fluid crosses over the border.

However to clear the effect of asymmetrical well locations, for the same production constraints, the distance of wells to the border in region two is changed. The distance of wells in region two from boundary is a quarter of this distance in region one. The obtained results showed that whatever the well is closer to the boundary more fluid can be drawn from other side of the boundary. This effect is slower but more considerable in oil system and as illustrated in Figure 2 till the 6 years about 0.9 percent of OOIP is drawn to region two. However, after 6 years some oil will return to its primary region because of the superposition of the pressure waves. The pressure of region one is dropped faster than two (higher pressure drop is propagated in region one), causing a positive potential to draw back the oil. In gas system, the displacement is small and happens in the first year of production and no gas return is occurred (**Figure 3**). In general, the pressure drop in regions with wells drilled far from border is faster and consequently in the long time its production will be limited.

3.1.3 Draining Horizontally

Drilling horizontal and hydraulically fractured wells are effective method to drain one region of a reservoir. In vertical well, pressure drop is applied to only one point of a reservoir while in horizontal hole it is imposed to one long line. This line can be parallel or perpendicular to the border. In the basic model, the wells in region one were completed about 1000 meters first parallel and second perpendicular to the border. Running the oil and gas models show drilling perpendicular can pull more oil and gas to cross the border (Figure 4 and Figure 5). In the oil model, the cross border fluid is started from the beginning and stopped after 10 years of production (Figure 4) while in the gas system the migration of gas and condensates have different behavior. As shown in Figure 5, gas and its associated condensates cross the border in early years with high slope, but then it is stopped for a long time because horizontal and vertical wells are producing with the same constraints. The gas migration is sharply kicked off after 40 years when reservoir pressure declines and resulting in a production drop of vertical wells while horizontal wells maintain their constrained production rate. Therefore, gas and its associated condensate migrate towards horizontal wells while some portion of condensates are formed and left behind in the original region. These results emphasize on importance of rock mechanical and tectonic study of the shared fields. Because drilling horizontal wells perpendicular to possible fractures networks or fracturing the formation can have big effect on long term well performance.

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3.2 Intrinsic Reservoir Characteristics

3.2.1 Reservoir Dip

The existence of slope can take gravity into consideration and change the direction of fluid movement. This parameter in the same well production constraints can move the fluid towards the downside of the reservoir.

To observe the effect of slope on reservoir performance, for the same production constraints, the model was dipped 5 degrees in such a way that country one is on the downside and country two is at the crest. In the oil system, one percent of reserve moved downside of the reservoir during the first three years of production but migration is stopped for the rest of production years (**Figure 6**). For a gas system shown in **Figure 7**, the gas displacement remain constant for first five years of production before increases steadily to just above 1.2 percent of the OGIP in the end of 50 years. Moreover, changing reservoir dips from 5 to 10 degree in the oil system can double the rate of migration while in gas system it is tripled. In other words the gas tendency to move towards the downside of the reservoir is continuous and more than the oil system.

3.2.2 Formation rock properties

In the basic model, different permeability of 10 and 40 millidarcy are considered for regions one and two respectively. By considering direct relation between permeability and diffusivity coefficient, this heterogeneity is expected to have an obvious effect on the crossing border fluid. With modeling the process, for equal production of the oil system (**Figure 6**), fluid moves from low permeability region (region one) towards high permeable region (region two) with a subtle slope migrating just above one percent of oil. In the gas system (**Figure 7**), gas displacement is slow till the year 35 when starts to increase with a sharp slope to just above one percent of reserve in the year 50. With investigating pressure change through the reservoir, it is found out that the movement of pressure drop wave increases with permeability. Therefore, in high permeability region, the pressure drop reaches the boundary sooner and causes the fluid migration towards itself, while the pressure drop in low perm region is slow and fluid has lower moving tendency.

Other influential intrinsic property of rock is porosity. Porosity effect on production can be discussed in two perspectives. First, a region with low porosity has less original fluid in place and second, according to **equation (3)**, low porosity regions (or thin productive formation) has higher diffusivity coefficient causing the pressure drop to feel the boundary sooner. This is resulted in pulling the fluid from high porous region. Therefore the effect of low porosity is the same as high permeability region. In constructed model regions one and two with 10 and 20 percent porosities (similar permeabilities) are considered and simulation is run. As shown in **Figure 6**, for the same production constraints, oil migrates from a high porous to a low porous region because higher pressure drop is imposed and travelled faster in low porous region. Comparing oil and gas migration in **Figure 6** and **Figure 7** shows oil displacement from high to low porous region stabilizes at one percent, while gas displacement is continuously increasing. This

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is because gas has higher potential to compensate the higher pressure drop in low porous region.

3.2.3 Natural pressure support

The existence of an aquifer, its strength and its extension has direct effect on recovery from a shared reservoir. In general, an aquifer depends on its strength in pressure maintenance of a region and its applied direction can have positive and negative effect on production of the region. When an edge water drive existed, some pressure drop is compensated and fluid is swept towards production wells and is kept the production constant for a longer period. Swept region with aquifer has high fluid recovery; however the aquifer can push all the recoverable fluid towards producing wells and also to neighborhood country. In **Figure 6**, the aquifer effect is presented as the strongest factor in pushing the oil towards the adjacent region, but in **Figure 7** the effect of aquifer is not so strong in a gas system probably due to inherit property of gas in compensating the pressure drop of the whole reservoir.

4. PASO gas field Case Study

PASO is a giant share gas field located in the south of Iran neighboring with Qatar country with a total Original Gas in Place (OGIP) of 51 trillion cubic meter and 47 billion barrels gas condensate. The formation has 155 km length and 75 km width and 435 meters thickness. About 38 percent of the formation is situated inside the Iran border. The formation has a slope of 0.5 degree in south-north and 0.6 degree slope in west-east directions. The original reservoir pressure is 5290 psi with good permeability and porosity distribution. The top view structure of the field is shown in **Figure 8** with the already drilled wells in both side of the border. Different development phases have been defined in both countries resulting different production rate in each side of the border. The neighbor country started the production in 1991 and with permanent investment and employing big oil and gas companies in 2010 their production reached to just below 500 million cubic meters per day (**Figure 9**). However, Iran has been left behind and started the production in 2002 and produced always lower than its neighbor. The development in Iranian border continued and consequently the production reached to 130 million cubic meters in 2011. As a result of different production kick off and production rate in both side of the border and also the drilling location of the wells (more wells in Qatar border drilled close to the border), some gas is migrating towards Qatar region. Red circle-line in **Figure 9** shows the cumulative migration of gas from Iran to neighborhood region. The migration started when the pressure drop of one region is felt in the border. Therefore, Qatar started the development of phases which are close to the border earlier. The migration is detected in the model shown in **Figure 8** as a fade green color is slowly moving towards the neighborhood region (to the left side of the border). Huge investment is allocating by both country to drain this field as much as possible. Applying the simple basic rules proved in this paper may help to compete in obtaining more profit from shared reservoirs. Iran should not stop production and development under any circumstances. The development phases and drilling horizontal wells close to the border should be in priority. The existence of is aquifer is a concern for Iran that has the lower percentage of the reservoir. Reservoir has a slight slope so the gravity cannot play a major role in cross over fluid. Accurate sedimentlogy study and drilling through high permeability and thin

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sections of the reservoir can compensate some of the migrated gas and associated condensates.

5. Results and Discussion

In order to prevent fluid crossing border, the shared reservoirs should be well characterized in the first place. Knowledge of porosity and permeability distribution (including fracture network), existence of aquifer and dip of reservoirs are among the intrinsic reservoir parameters that can have influence on the recovery of both countries. Drilling a well in high permeable and low porosity zone can create a potential to one country's fortune. Strong aquifer can push the oil towards more drained section of the reservoir and increase the recovery. If one country starts the production late, one section of oil or gas can be swept by water to neighborhood country. The slope of the reservoir is also important specially when dealing with undersaturate oil reservoirs. After production of each country the total reservoir pressure is dropped and the gas cap is formed mainly in the crest of the reservoir. So the country which has the crest losses some oil production.

Defining proper development scenario is the second important stage in managing shared reservoirs. Earlier production kick-off not just get a country ahead of production but also can cause a local pressure drop that can pull the neighborhood reserve towards itself. Wells should be drilled as much close to the border as possible to be able to apply enough pressure drop to the border. Drilling horizontal well and intersecting fracture networks or hydraulic fracturing operations are the advantages that can dominate a large drainage area around the wellbore.

Noticing all factors in a shared field, there is a tight competition with neighboring country not just in investing sooner but also collecting reservoir data. The triumph is whose to invest more and characterize the reservoir accurately to plan an appropriate development scenario.

A country that has lost the ground of production should try to apply both reservoir characterization data and proper field development plan to first stop losing more reserve and to compensate the possible fluid migrated towards neighborhood country.

6. Conclusions

Knowledge of the effect of different parameters on pressure drop is a key point in management of fluid in the border of a shared reservoir and consequently leading to optimum recovery. Sooner production kick-off is important but there are other parameters that have influence on fluid management of common fields. This study is important especially for Iran which has lots of shared oil and gas fields and the following conclusions are drawn:

1- Data sharing and integration of reservoir study between two neighborhood countries are the ideal approach to maximize the common hydrocarbon field recovery.

2- Superposition of pressure drops should be managed in the border of reservoir to prevent fluid migration to neighborhood territory.

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3- Appropriate reservoir characterization and proper development plan are the key elements in management of shared reservoirs.

4- Production overtaking, higher production, drilling horizontally and close to the border are the operational factors to draw the fluid in favor of one country.

5- The country that shares the downside section of a reservoir, high permeable and low porosity (thin formation) can apply more pressure drop to the border. However, the existence of an aquifer pushes the oil towards the neighborhood territory.

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NOMENCLATURE

A = Cross sectional area, acre

c = constant conversion coefficient

c_t = total compressibility of media

k = permeability, millidarcy

P = pressure, psi

q = Liquid rate, barrels per day

r_e = radius of investigation, meter

t = time, hours

x = length, meter

μ = viscosity, centipoise

ψ = fluid potential, psi

ϕ = porosity of rock, dimensionless

η = diffusivity coefficient

Acronyms

OGIP= Original Gas In Place, Cubic meter

Psi= pound per square inch, dimension of pressure

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Table 1: Daily production rate of both countries from common fields [5]

Fields Common with	Number of Common Fields	Daily Production of Iran	Daily production of Neighbor
Qatar (South pars gas zone)	1	210 million cubic meter	360 million cubic meter
Qatar (South pars oil zone)	1	zero	450,000 bbls
Iraq	12	130,000 bbls	295,000 bbls
UAE	7	56,000 bbls	136,000 bbls
Saudi Arabia	4	42,000 bbls	450,000 bbls

Table 2: Rock and fluid properties of an oil reservoir model

Length(km)	20	Solution Gas(scf/stb)	1130
Width(km)	8	Compressibility(psia-1)	10-6
Height(m)	100	Water Density(lbm/cft)	Lbm/cft
Porosity	13	Oil density(lbm/cft)	44.98
Permeability(md)	40	Gas Density(lbm/cft)	0.0702
Swr	0.2	Oil Viscosity (cp)	0.16
Sor	0.19	Water Viscosity(cp)	0.96
Sgr	0.1	Gas Viscosity(cp)	1
Bubble Point(psi)	2800		

Table 3: Rock and fluid properties of a gas reservoir model

Length(km)	20	Solution Gas(scf/stb)	1130
Width(km)	8	Compressibility(psia-1)	10-6
Height(m)	100	Water Density(lbm/cft)	Lbm/cft
Porosity	13	Oil density(lbm/cft)	44.98
Permeability(md)	40	Gas Density(lbm/cft)	0.0702
Swr	0.2	Oil Viscosity (cp)	0.16
Sor	0.19	Water Viscosity(cp)	0.96
Sgr	0.1	Gas Viscosity(cp)	1
Bubble Point(psi)	2800		

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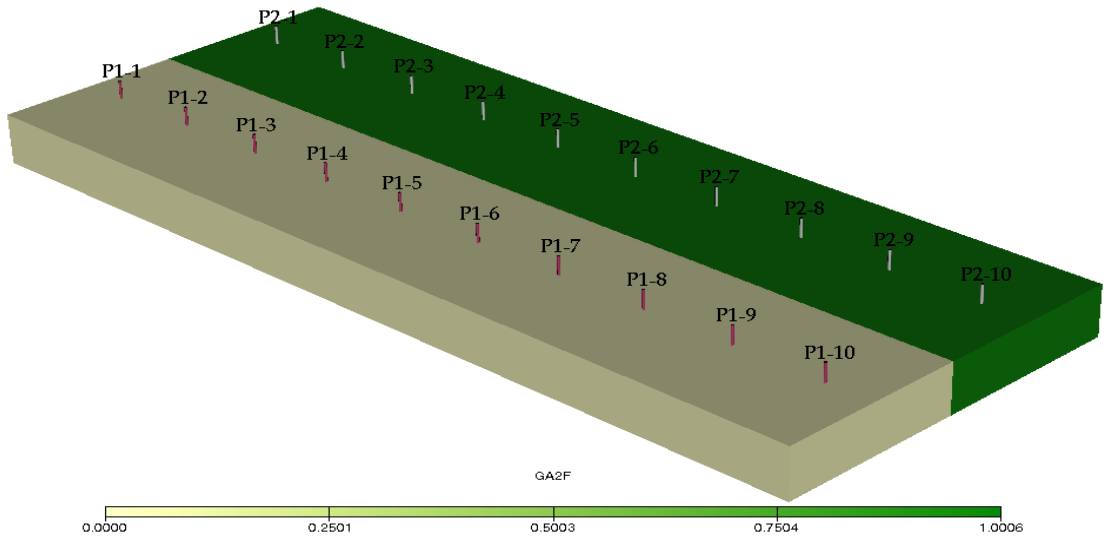

Figure 1: The basic model: a simple sector model divided into two regions both side of the border with 10 wells in each side

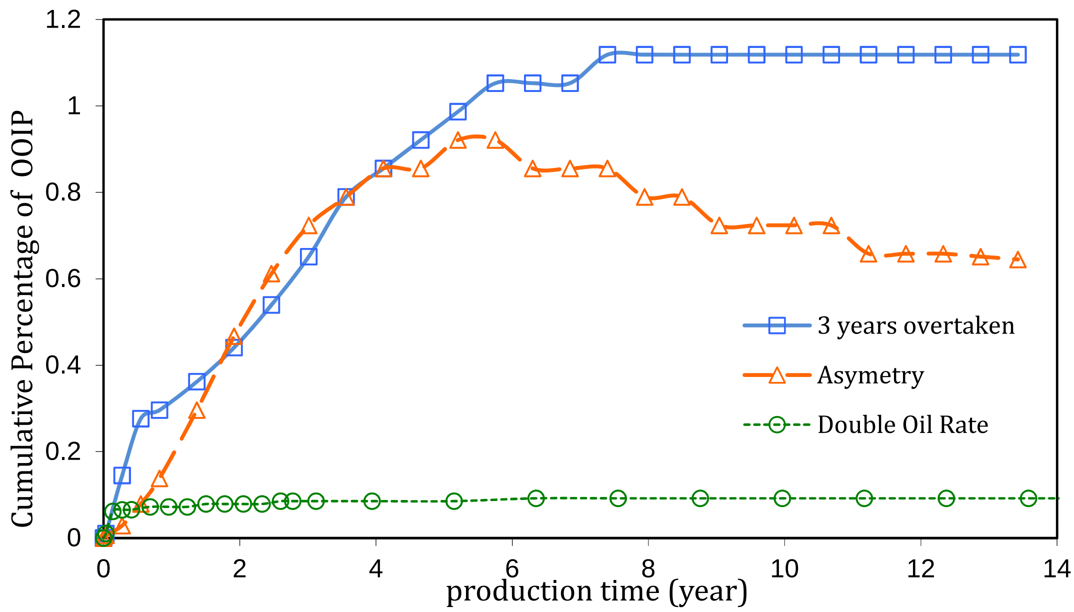

Figure 2: The effect of field development plans on cross-border oil migration

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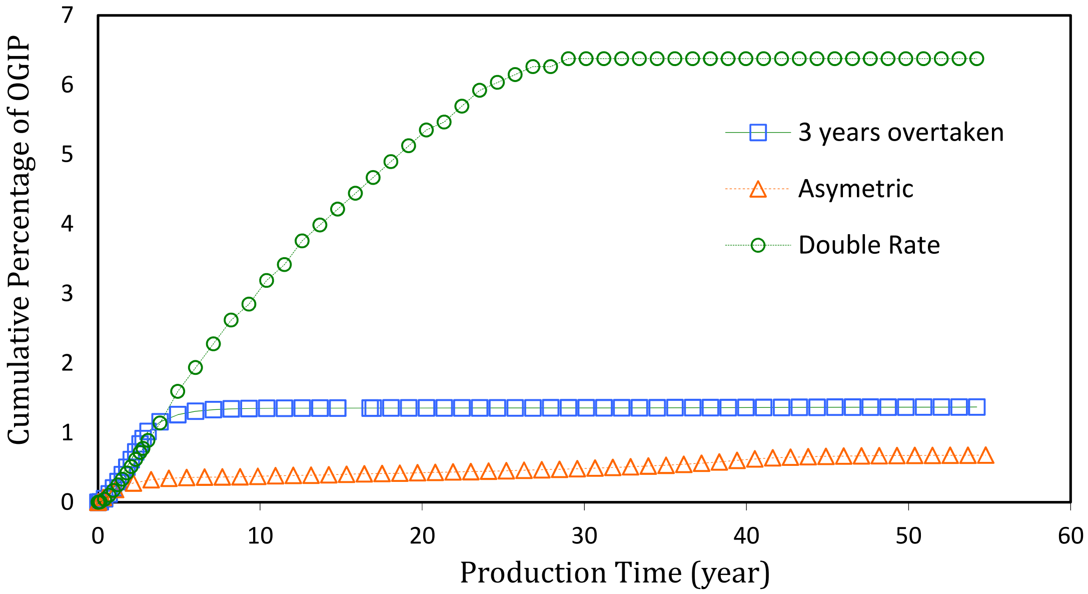

Figure 3: The effect of field development plans on cross-border gas migration

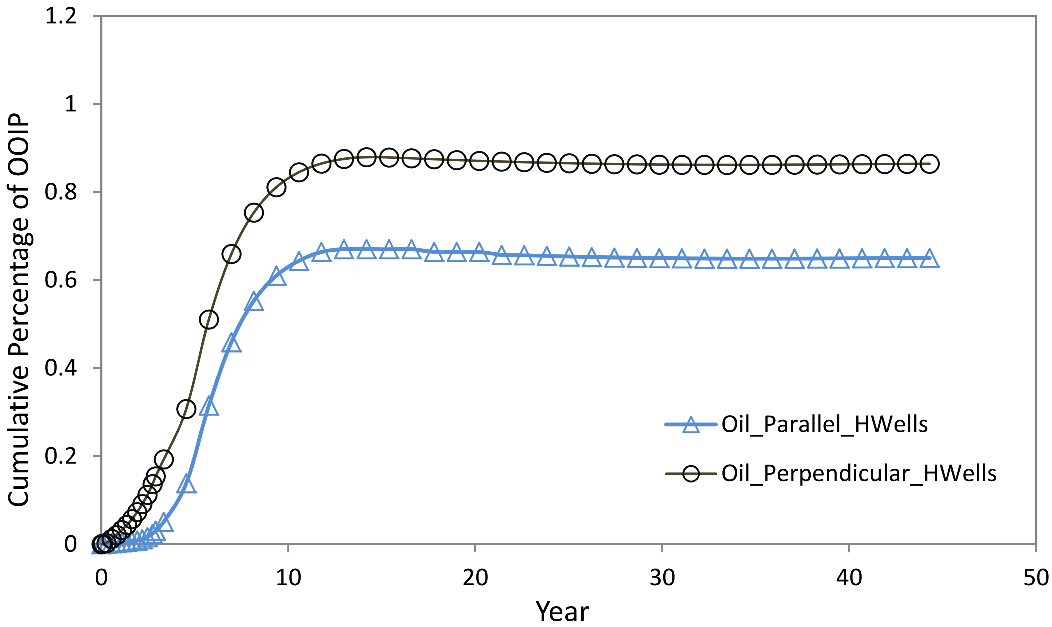

Figure 4: Fluid migration in oil fields when horizontal wells are parallel and perpendicular to the border

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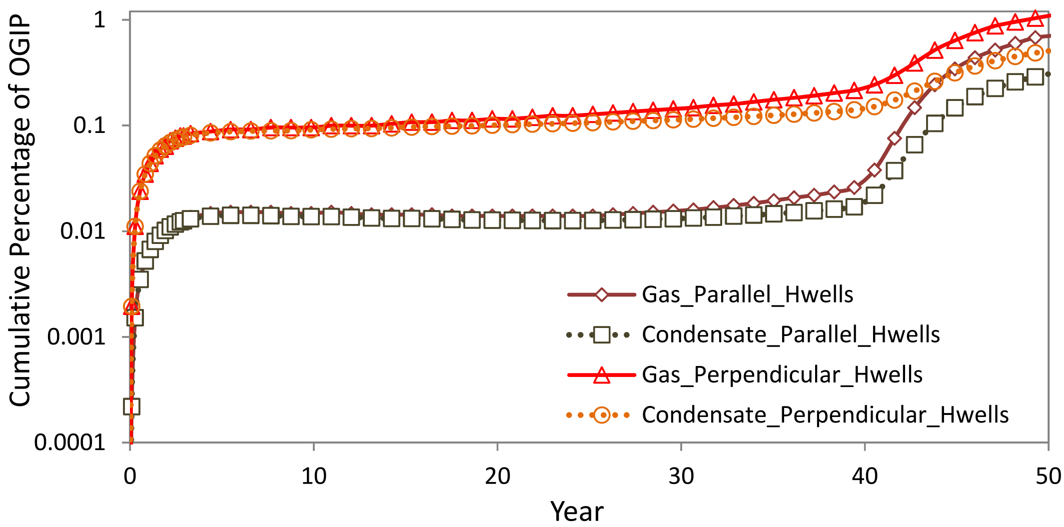

Figure 5: Fluid migration in gas fields when horizontal wells are parallel and perpendicular to the border

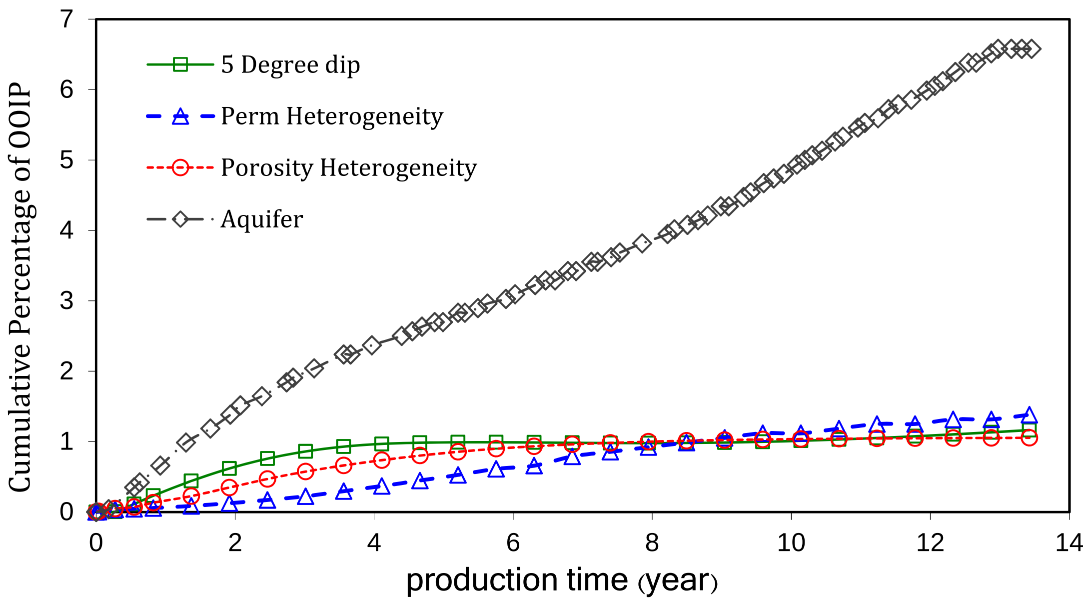

Figure 6: The effect of reservoir characteristics on cross-border oil migration

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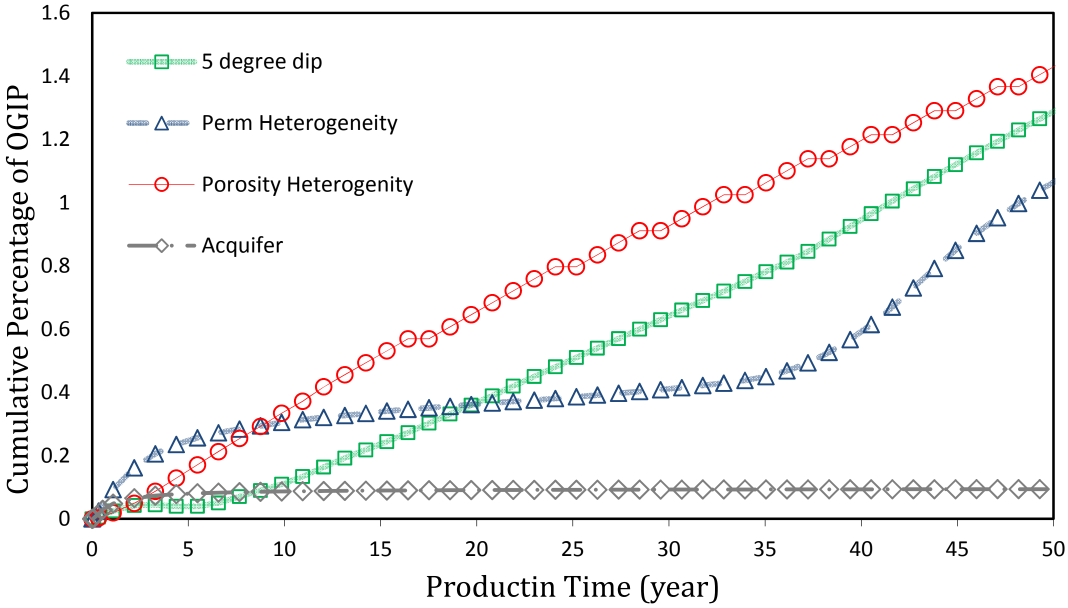

Figure 7: The effect of reservoir characteristics on cross-border gas migration

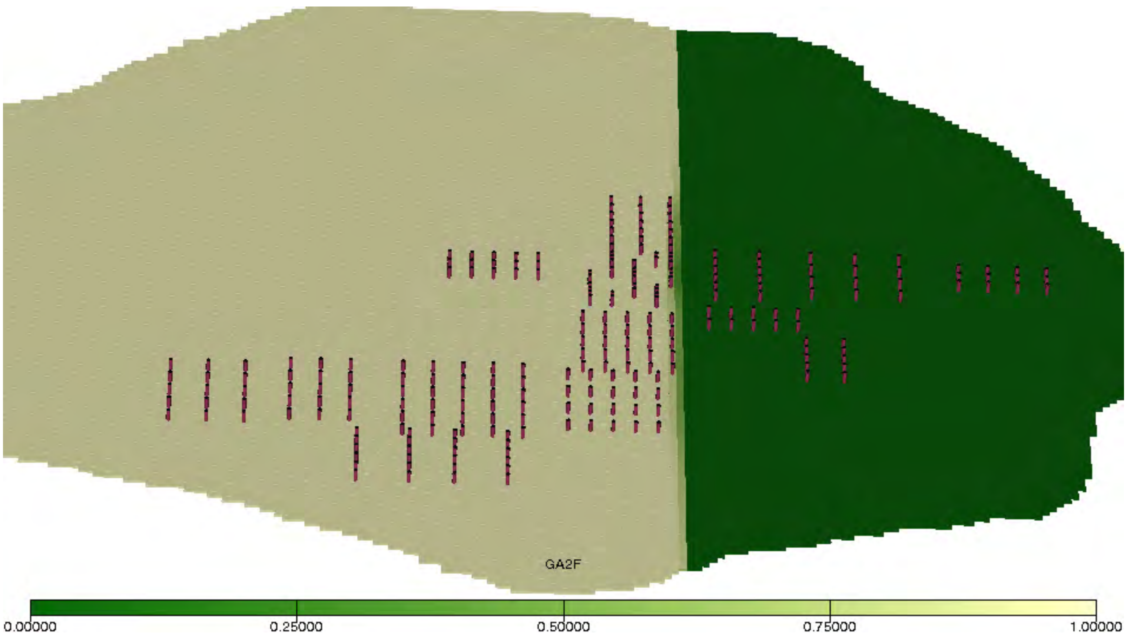

Figure 8: The model of PASO gas field: gas is migrated to most producing side (fake green color in the left side of the border).

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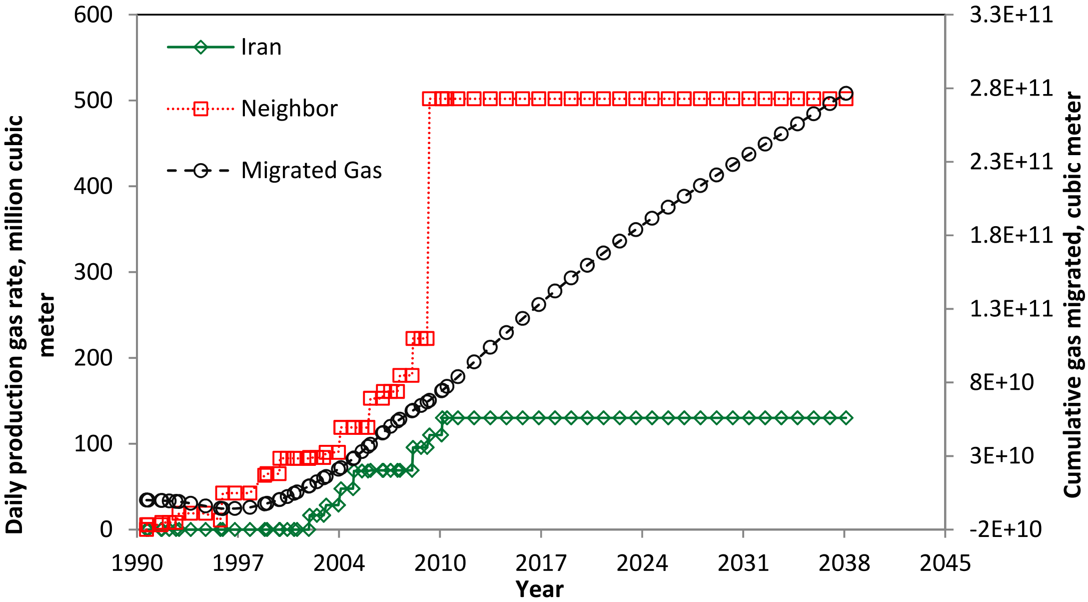

Figure 9: Gas production of Iran and neighbor from PASO gas field and the cumulative cross border gas migration

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