

PRODUCTIVITY INDEX IN HORIZONTAL WELL

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ABSTRACT

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The work in this project studied the productivity index of horizontal wells in the Mabruk (west Mabruk) oil field. Different aspects of horizontal wells were reviewed; including drilling and completion technologies, limitations and applications. Different method were used to calculate productivity index under steady state (e.g ,Borisov's ,Joshi's ,Giger and Renard and Dupuy ,methods) and pseudo steady state conditions (e.g. the Mutalik et al , Babu and Odeh , Kuchuk et al methods) of the horizontal well were also reviewed. The factors effect pressure drops between the reservoir and the wellbore such as well length, permeability, reservoir thickness, drainage area, fluid viscosity, and perforation percentage. Horizontal drilling has been used successfully to Increase the productivity of reservoirs; many formulas can be used to compute the productivity of horizontal compared to vertical ones. The objectives of this work are to identify the different flow regimes in Horizontal Wells and reservoir parameters that are required to calculate the Productivity Index and to compare the Productivity between the different methods in Horizontal Wells.

1.0 Introduction

Horizontal drilling is the process of drilling and completing, for production, a well that begins as a vertical or inclined linear bore which extends from the surface to a subsurface location just above the target oil or gas reservoir called the "kickoff point", then bears off on an arc to intersect the reservoir at the "entry point", and, thereafter, continues at a near-horizontal attitude tangent to the arc, to substantially or entirely remain within the reservoir until the desired bottom hole location is reached.

Horizontal drilling has become extremely popular with operating companies seeking to obtain higher productivity index, reduce water and gas conning, and intersect natural fractures and to improve well economics.

Because of the great experience gained and improvement made on horizontal well technology in the past 25 years, the studies refer the increment in the cost of drilling a horizontal well was only (8%) higher per foot compared to the cost of drilling a vertical well.

The horizontal drilling started in Libya (1995), many companies now using this way to drill many wells to productivity increase (2-3) times, compared with vertical drilling. void many problems, like water conning or other problems and to reduce number of wells drilled in the field.

Now in Libya, some of the horizontal wells are cased or completed as open hole, according to the reservoir characteristics and the length of the horizontal section may be between (600-3500) ft.

In general, a horizontal well is drilled parallel to the reservoir bedding plane. Strictly speaking, a vertical well is a well which intersects the reservoir bedding plane at 90'. In other words, a vertical well is drilled perpendicular to the bedding plane as shown in the 1(1).

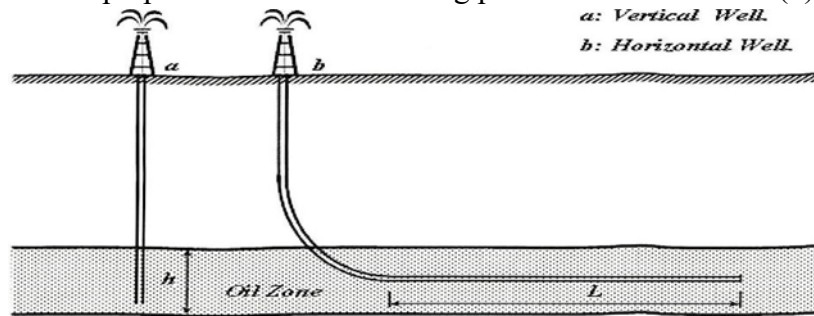


Figure 1. A Schematic of a vertical well drilled perpendicularly to the bedding plane and a Horizontal well drilled parallel to the bedding plane.

1.1 Advantages of Horizontal Drilling:

1. Higher sweep efficiency and larger injected area.
2. Increased drainage area per well.
3. Lower injection pressure requirement for injecting fluids compared to vertical wells.
4. Reduced unfavorable influence from gas cap drive or active aquifer drive mechanisms.
5. Less environmental impact due to fewer wells needed to be drilled for accessing a large formation area below a small land or an offshore platform.
6. Large volume of the reservoir can be drained by each horizontal well.
7. Higher productions from thin pay zones.
8. Horizontal wells minimize water and gas zoning problems.
9. In high permeability reservoirs, where near-wellbore gas velocities are high in vertical wells, horizontal wells can be used to reduce near-wellbore velocities and turbulence.
10. In secondary and enhanced oil recovery (EOR) applications, long horizontal injection wells provide higher injectivity rates.
11. The length of the horizontal well can provide contact with multiple fractures and greatly improve productivity.

1.2 Disadvantages of Horizontal Drilling:

1) Hole cleaning:

As the drill string lies on the low side of the hole, beds of cuttings build up around the bottom of edge of the drill string, these can be very hard to shift.

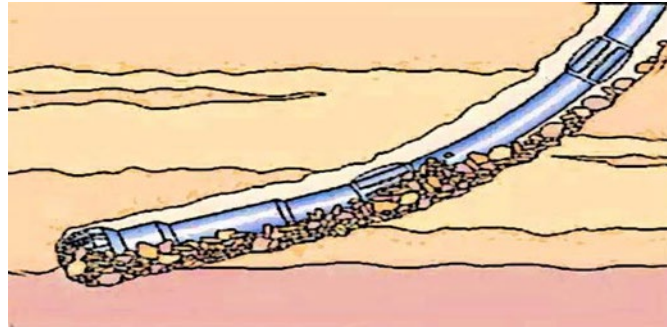


Figure 2. Shows poor hole cleaning.

2) Frictional forces:

The power needed to turn the drill string or to pull it out of the hole are higher on horizontal well than on a normally deviated or vertical well.

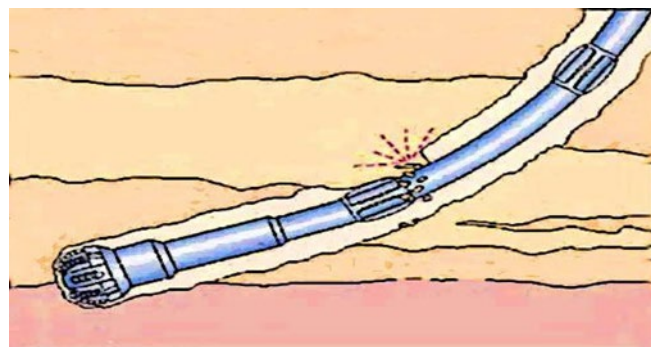


Figure 3. Shows friction force.

3) Accurate navigation in the reservoir:

Navigation within the reservoir is relative the reservoir characteristics and not computed according to inclination and azimuth only.

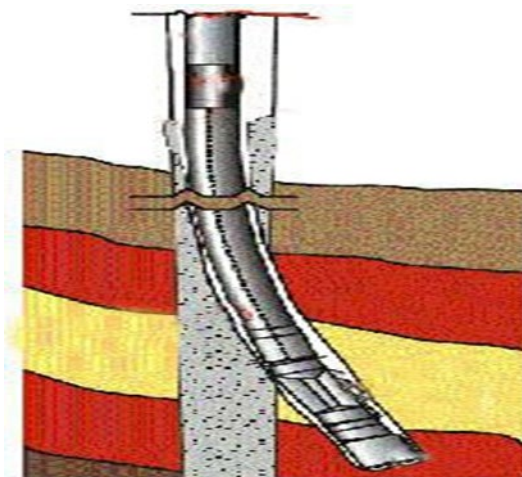


Figure 4. Shows navigation in the reservoir.

1.3 Applications of Horizontal Drilling:

The reservoirs that maybe considered as possible candidates for horizontal drilling are:

1. Reservoirs that may have potential water/gas-coning problems.

2. Tight reservoirs (permeability \ll 1 millidarcies (md)).
3. Natural vertically fractured reservoirs.
4. Economically inaccessible reservoirs.
5. Heavy oil reservoirs.
6. Channel and reef sand reservoirs.
7. Coal bed methane reservoirs.
8. Thin reservoirs.
9. Layered reservoirs with high dip angle.
10. Partially depleted reservoirs.

1.4 Drilling Techniques:

The drilling techniques to drill horizontal wells and drain holes are classified into four categories, depending upon their turning radius. Turning radius is the radius that is required to turn from the vertical to horizontal direction.

The four categories are:

Table 1. Type of different drilling techniques:

Type	Radius (ft)	Long (ft)	Angle
Ultra-short radius	1-2	100-200	45°-60° / 100 ft
Short radius	20-40	100-800	2°-5° / 100 ft
Medium radius	300-800	1000-4000	6°-20° / 100 ft
Long radius	≥ 1000	1000-4000	2°-6° / 100 ft

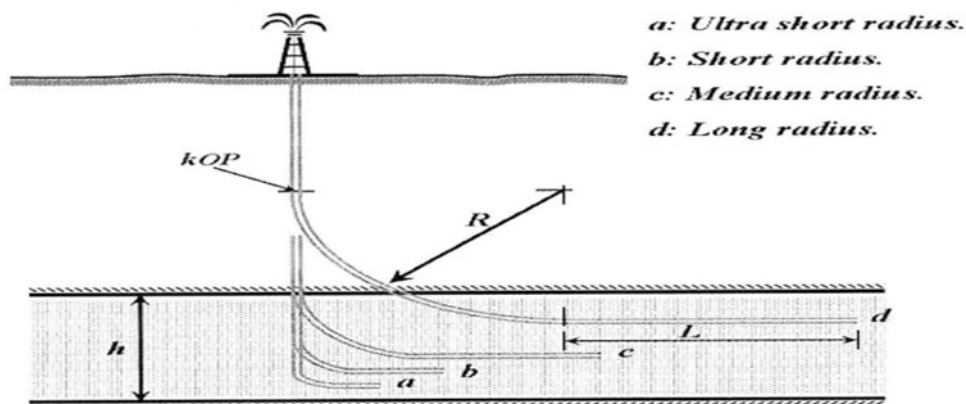


Figure 5. Schematic of different drilling techniques.

1.5 Completion Techniques:

The completion phase of a well development is a term generally used for a well that is prepared for production after drilling is completed. It follows therefore that during the exploration, appraisal and development testing of wells, a temporary completion is used as the well is temporarily produced to gain valuable reservoir data for the future development of the field.

There are two main categories of completions:

1. Open-hole completion:

An open-hole completion is when the well is drilled to the top of the target formation and the casing is cemented at this stage.

Drilling is continued across the target formation and then the well is completed and produced. Open-hole completions are only possible in "competent" rocks that will hold their form and not cave in or crumble so called hard rock environments. This technique is generally associated with many apparent disadvantages:

1. No possibility for selectively producing or treating different zones.
2. Limited control of water or gas encroachment.
3. Cased-hole completion:

A cased hole completion is when the well has been cased and cemented across the target formation and requires shaped charge perforation to achieve communication between the formation and the wellbore. This is the most common form of completing wells.

2. PRODUCTIVITY INDEX:

1. Overview: It's measure the ability of the well to produce; the productivity index is the ratio of the total liquid flow rate to the pressure drawdown.

The productivity index is generally measured during a production test on the well.

The well is shut-in until the static reservoir pressure is reached. The well is then allowed to produce at a constant flow rate of (q) and a stabilized bottom-hole flow pressure of (P_{wf}). In order to accurately measure the productivity index of a well, it is essential that the well is allowed to flow at a constant flow rate for a sufficient amount of time to reach the pseudo steady-state as illustrated in **Figure (2-1)**. The figure indicates that during the transient flow period, the calculated values of the productivity index will vary depending upon the time at which the measurements of (P_{wf}) are made.

The main assumption is that relationship between the drawdown and the rate is often assumed to remain constant with time. These ideas have been used to predict the production rate under various operating condition, we will see that this assumption is true only under special conditions (**Steady-State Flow**).

In practice the relationship between the drawdown and the flow rate depending on the boundary effects of the well drainage (**flow regimes**).

When a reservoir is bounded with a constant pressure boundary (**such as a gas cap or an aquifer**), flow reaches the steady-state regime after the pressure transient reaches the constant pressure boundary. Rate and pressure become constant with time at all points in the reservoir and wellbore once Steady-State flow is established **Figure (2-1)**. Therefore, the productivity index during steady-state flow is a constant i.e.

($dP/dt = 0, dJ/dt = 0$).

During the pseudo steady-state regime, (**no-cross flow boundaries in other words when the pressure transient reaches all boundaries after drawdown for a sufficiently long time**), the rate of pressure decline is almost identical at all points in the reservoir and wellbore. Therefore, the difference between the average reservoir pressure and pressure in the wellbore approaches a constant (not changing with time) as shown in **Figure (2-1)**, i.e. $\left(\frac{d}{dt}(\Delta P) = constant, dJ/dt = constant\right)$.

In the definition of pseudo-steady state productivity index, the average reservoir pressure is used instead of the initial reservoir pressure and hence the productivity index is basically constant.

Each flow regimes are applicable at different times after the start of production and for different, assumed boundary conditions hence several solutions are available in the literature for the productivity index under each flow regime in vertical or horizontal well either in isotropic reservoir and/or anisotropic reservoir.

Since most of the well life is spent in a flow regime that is approximating the pseudo steady-state the productivity index is valuable methodology for predicting the future performance of

wells. Further, by monitoring the productivity index during the life of a well, it is possible to determine if the well has become damaged due to completion, work over, production, injection operations, or mechanical problems. If a measured (J) has an unexpected decline, one of the indicated problems should be investigated.

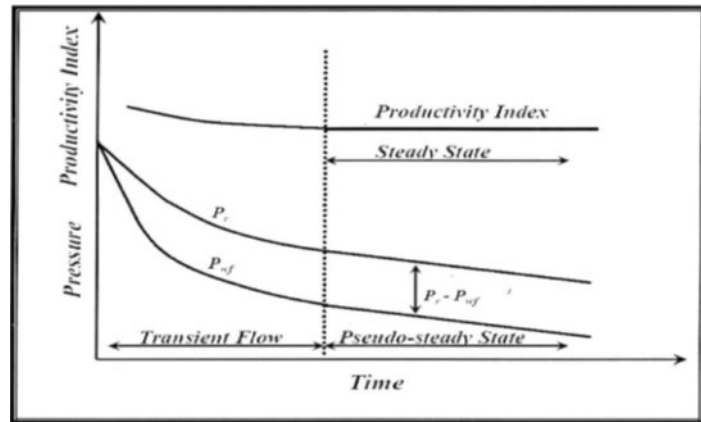


Figure 6. Productivity Index during Flow Regimes⁽⁶⁾.

2.0 Methodology

2.1 Steady-State Solutions:

Steady State Isotropic Condition:

✓ Borisov	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h h / (\mu_o \beta_o)}{\ln\left(\frac{4r_{eh}}{L}\right) + \left[\left(\frac{h}{L}\right) \ln\left(\frac{h}{2\pi r_w}\right)\right]}$
✓ Giger	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h L / (\mu_o \beta_o)}{\left[\left(\frac{L}{h}\right) \ln(C)\right] + \ln\left(\frac{h}{2\pi r_w}\right)}$
✓ Joshi	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h h / (\mu_o \beta_o)}{\ln(R) + \left(\frac{h}{L}\right) \ln\left(\frac{h}{2r_w}\right)}$
✓ Renard And Dupuy	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h h / (\mu_o \beta_o)}{\cosh^{-1}(X) + \left(\frac{h}{L}\right) \ln\left(\frac{h}{2\pi r_w}\right)}$

Steady-state solutions, i.e pressure at any point in the reservoir does not change with time.

Darcy's law for flow through porous media:

$$q = \frac{-kA}{\mu} \frac{\Delta P}{\Delta x}$$

2.2 Steady-State Productivity of Horizontal Wells:

a- Isotropic reservoirs ($k_h = k_v$):

Productivity ratios:

$$\text{Productivity ratios} = \frac{J_h}{J_v}$$

where:

J_v = Productivity index of a vertical well, **STB/day/psi**.

Areal productivity index:

$$\text{Areal productivity index} = \frac{J_h}{\text{acre}} \text{ STB/day/(psi.acre)}$$

b- Anisotropic reservoirs ($k_h \neq k_v$):

If we have a reservoir with different horizontal and vertical permeabilities, then we can write the Laplace equation which represents steady-state flow as:

$$k_h \left(\frac{\partial^2 P}{dx^2} \right) + k_v \left(\frac{\partial^2 P}{dz^2} \right) = 0$$

This can be rewritten as:

$$\left(\frac{\partial^2 P}{dx^2} \right) + \left(\frac{\partial^2 P}{dz^2} \right) = 0$$

where:

$$\hat{z} = z\sqrt{k_h/k_v}$$

And effective reservoir permeability (k_{eff}) is defined as:

$$k_{eff} = \sqrt{k_h k_v}$$

Thus, the influence of reservoir anisotropy can be accounted for by modifying the reservoir thickness as:

$$\hat{h} = h\sqrt{k_h/k_v}$$

• Giger	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h / (\mu_o \beta_o)}{\left(\frac{1}{\hat{h}}\right) \ln(X) + \left(\frac{\beta^2}{L}\right) \ln\left(\frac{h}{2 r_w}\right)}$
• Joshi	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h h / (\mu_o \beta_o)}{\ln(R) + \left(\frac{\beta h}{L}\right) \ln\left(\frac{\beta h}{2 r_w}\right)}$
• Renard and Dupuy	$J_h = \frac{q_h}{\Delta P} = \frac{0.007078 k_h h / (\mu_o \beta_o)}{\cosh^{-1}(X) + \left(\frac{\beta h}{L}\right) \ln\left(\frac{h}{2\pi r_w}\right)}$

2.3 Pseudo-Steady State Solution:

Pseudo-steady state begins when the pressure disturbance created by the producing well is felt at the boundary of the well drainage area. In other words, when the fluid mass situated at the drainage boundary starts moving towards the producing well, pseudo-steady state begins. This pseudo-steady state is also described as semi-steady state or depletion state. The name depletion state is probably the most appropriate, because it tells us that the reservoir has reached a point where the pressure at all the reservoir boundaries and also the average reservoir pressure will decrease over time as more and more fluid is withdrawn from the reservoir.

2.4 Shape Factors of Horizontal Wells:

For horizontal wells, in addition to the side boundaries of the areal drainage plane, the top and bottom reservoir boundaries also influence well productivity. Thus, a horizontal well shape factor depends upon:

1. drainage area shape, i.e., ratio $\left(\frac{2x_e}{2y_e}\right)$
2. Well penetration, $\left(\frac{L}{2x_e}\right)$
3. Dimensionless well length, $\left(L_D = \frac{L}{2h} \sqrt{k_v/k_h}\right)$.

2.5 Horizontal Well Pseudo-Steady State Productivity Calculations:

Babu and Odeh Model

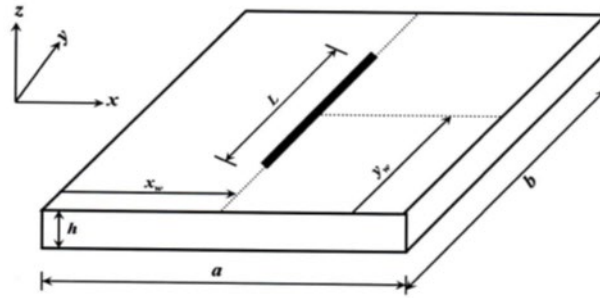


Figure 7. A schematic of a horizontal well located in a rectangular Drainage volume.

✓ Mutalik	$J_h = \frac{0.007078 k h / (\mu_o \beta_o)}{\ln \left(\frac{r_e}{r_w} \right) - A' + S_f + S_m + S_{CA,h} - C + (Dq)}$
✓ Babu and Odeh	$J_h = \frac{0.007078 (2X_e) \sqrt{k_y k_v} / (\mu_o \beta_o)}{\ln \left(\frac{\sqrt{A1}}{r_w} \right) + \ln C_H - 0.75 + S_R}$
✓ Kuchuk	$J_h = \frac{k_h h / (70.6 \mu_o \beta_o)}{F + \left[\left(\frac{h}{0.5L} \right) \sqrt{\frac{k_h}{k_v}} S_x \right]}$

3.0 Calculation & Results:

3.1 Productivity index Calculation :

A 1000-ft long horizontal well is drilled in reservoirs with the following
Table 2. Well Information

Well Orientation	Horizontal
Well Completion	Open Hole
Well Drilling Length, L	1447 ft.
Well Radius, r_w	0.5 ft.
Vertical Well Location, z_w	22.5 ft.
Vertical Section Spacing, A (avg)	120 acres

Table 3. Rock and Fluid Properties

Layer Net Thickness, h	45 ft.
Oil Formation Volume Factor, β_o	1.057 res bbl./STB
Oil Viscosity, μ_o	2.41 cp

Table 4. Reservoirs Properties Estimation using Well Test Analysis

Parameter	Results	Unit
k_v	33	Md
$k_h = k_x = k_y$	110	Md
k_v / k_h	0.3	Ratio
S	0	Unitless

3.2 Steady-State Productivity of Horizontal:

1-Borisov Method:

For Isotropic Reservoir

Table 5. Productivity ratio J_h / J_v

Methods	J_h STB/day/psi	Productivity ratio J_h / J_v	Areal horizontal Productivity index STB/day/(psi.acre)
Brisov	8.087	4.619	0.0337
Giger	8.291	4.735	0.0345
Renard and Dupuy	8.083	4.616	0.0337
Joshi	7.918	4.520	0.0330

Note: It is important to note that the above productivity index comparison assumes unstimulated vertical well.

For Anisotropic Reservoirs

The result are summarized below:

Table 6. Reservoirs Properties Estimation using Well Test Analysis

Horizontal well productivity index (J_h) STB/day/psi	
Methods	$k_v / k_h = 0.3$
Giger	10.123
Renard and Dupuy	7.708
Joshi	7.359

Note: For stimulating a horizontal well. Thus, preplanning of a horizontal well based upon geological, reservoir and drilling consideration is essential.

3.2.1 Pseudo Steady State Productivity:

A horizontal well drilled in an oil reservoir has the following parameters:

Table 7. parameters of Well (A46)

Horizontal well length, L (ft)	1447
Horizontal permeability, k_h (md) = k_x (md) = k_y (md)	110
Vertical permeability, k_v (md)	5
Oil formation volume factor, β_o (RB/STB)	1.2
Oil viscosity, μ_o (cp)	0.3
Reservoir thickness, h (ft.)	160
Wellbore radius, r_w (ft.)	0.365
Drainage radius of vertical wells, r_{ev} (ft.)	745
Drainage area of vertical wells, A (acre)	160

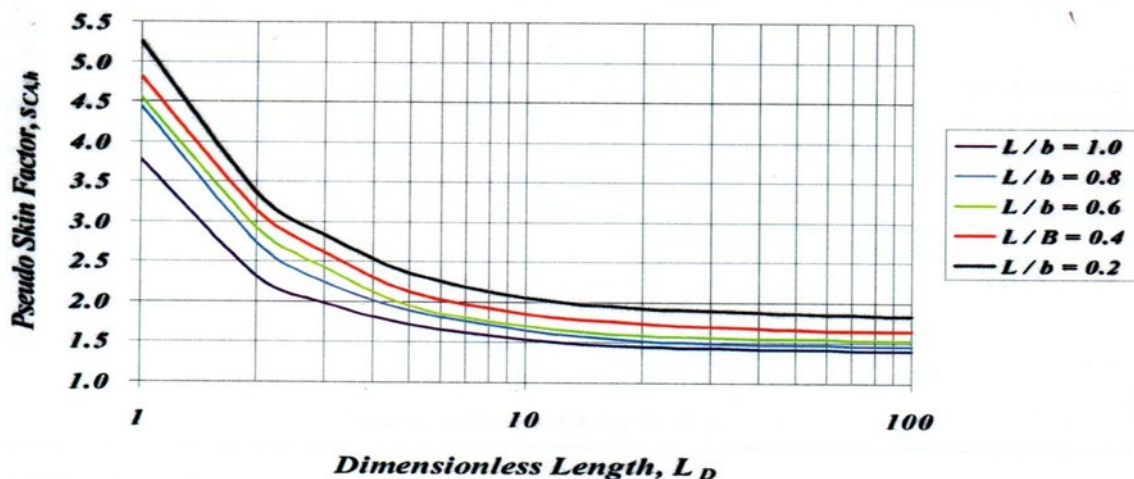


Figure 8. Shape related skin factor ,SCA,h for horizontal well in a square drainage area (b / a) = 1

3.3 Productivity index Calculation:

A 1741-ft long horizontal well is drilled in reservoirs with the following Information:

Table 8. Well Information:

Well Orientation	Horizontal
Well Completion	Open Hole , Slotted liner
Well Drilling Length, L	1741 ft.
Well Radius, r_w	0.375 ft.
Vertical Well Location, z_w	22.5 ft.
Vertical Section Spacing, A (avg)	120 acres

Table 9. Rock and Fluid Properties:

Layer Net Thickness, h	45 ft.
Oil Formation Volume Factor, β_o	1.057 res bbl./STB
Oil Viscosity, μ_o	2.41 cp

Table 10. Reservoir Properties Estimation using well Test Analysis:

Parameter	Results	Unit
k_v	29.7	Md
$k_h = k_x = k_y$	99	Md
k_v / k_h	0.3	Ratio
Skin	0.13	Unitless

Note: The Calculation and the Results of this Well it has summarized in the APPENDIX II.

3.4 Productivity index Calculation:

A 1994-ft long horizontal well is drilled in reservoirs with the following Information:

Table 11. General Information:

Company	MABRUK Oil Company
Field Name	West Mabruk
Well No	A-65
Drilling Date	24, Apr, 1997

Table 12. Well Information:

Well Orientation	Horizontal
Well Completion	Open Hole
Well Drilling Length, L	1994 ft.
Well Radius, r_w	0.5 ft.
Vertical Well Location, z_w	20 ft.
Vertical Section Spacing, A (avg)	120 acres

Table 13. Rock and Fluid Properties:

Layer Net Thickness, h	40 ft.
Oil Formation Volume Factor, β_o	1.057 res bbl./STB
Oil Viscosity, μ_o	2.41 cp

Table 14. Reservoir Properties Estimation using well Test Analysis:

Parameter	Results	Unit
k_v	7.8	Md
$k_h = k_x = k_y$	26	Md
k_v / k_h	0.3	Ratio
Skin	-0.23	Unitless

4.0 COMPARISON OF RESULTS:

Steady-State Productivity:

Table 14. A comparison of horizontal well productivities by the four methods for different values of (K_v / K_h)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	$k_v/k_h = 0.3$		$k_v/k_h = 1$	
	L=1447 ft	L=2000 ft	L=1447 ft	L=2000 ft
Brisov	Xxx	Xxx	8.087	10.156
Giger	10.123	14.305	8.291	10.840
Renard and Dupuy	7.708	9.706	8.083	10.136
Joshi	7.359	9.304	7.917	9.947

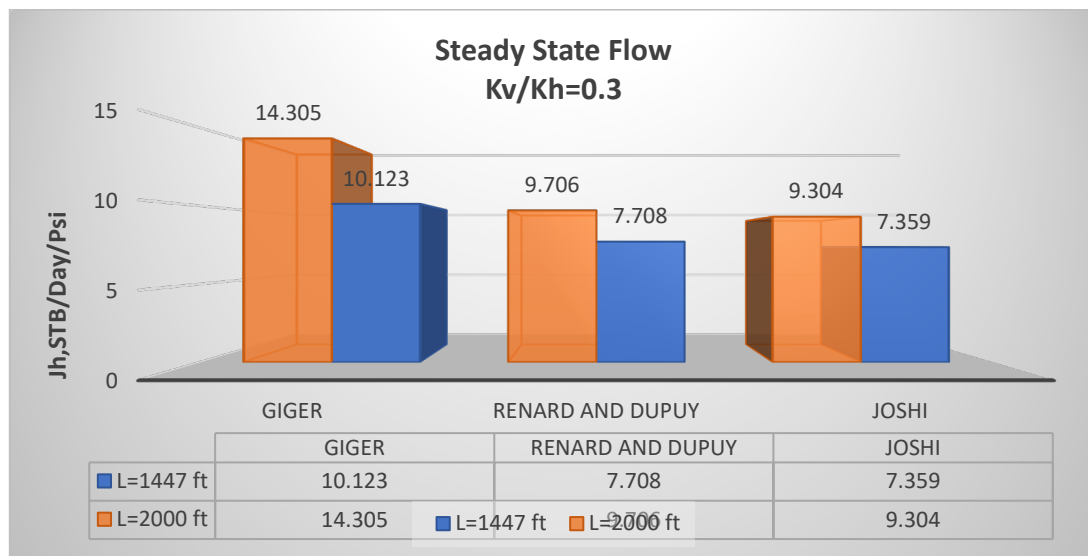


Figure 9. A comparison of horizontal Steady-State anisotropic Productivity of well (A 46).

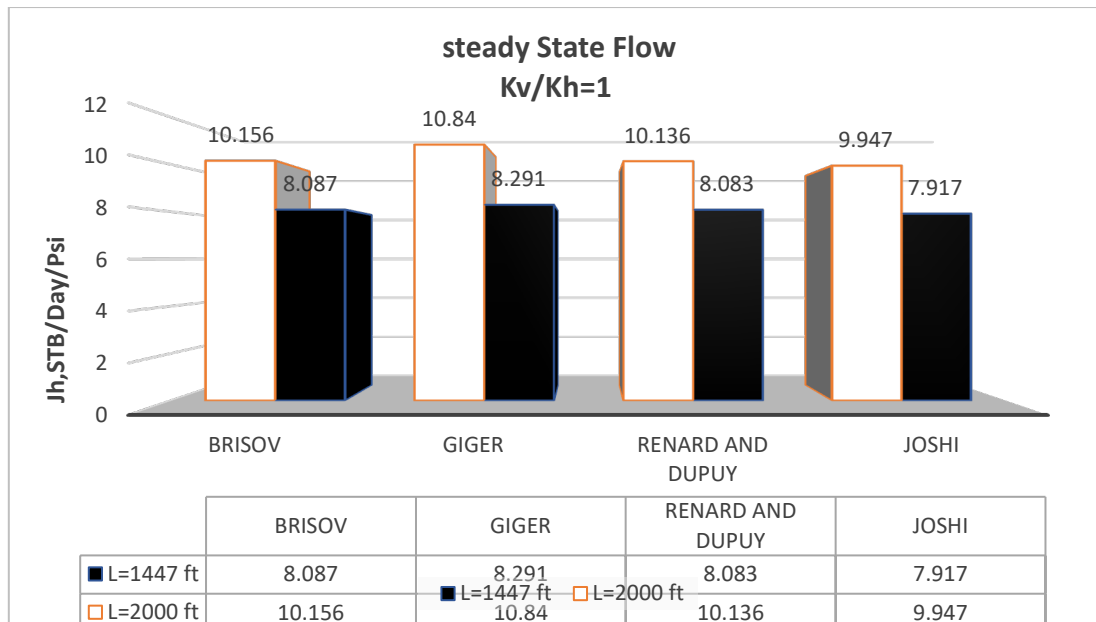


Figure 10. A comparison of horizontal Steady-State isotropic Productivity of well (A 46).

4.1 Pseudo Steady State Productivity of well (A46):

Table 15. A comparison of horizontal well productivity by the three methods for different values of (K_v / K_h).

Horizontal well productivity index (J_h) STB/day/psi				
Methods	kv/kh = 0.3		kv/kh = 1	
	L=1447 ft	L=2000 ft	L=1447 ft	L=2000 ft
Mutalik et al.	11.358	15.913	12.712	17.695
Babu and Odeh	10.000	13.249	10.555	14.088
Kuchuk et al.	11.169	15.264	11.971	16.348

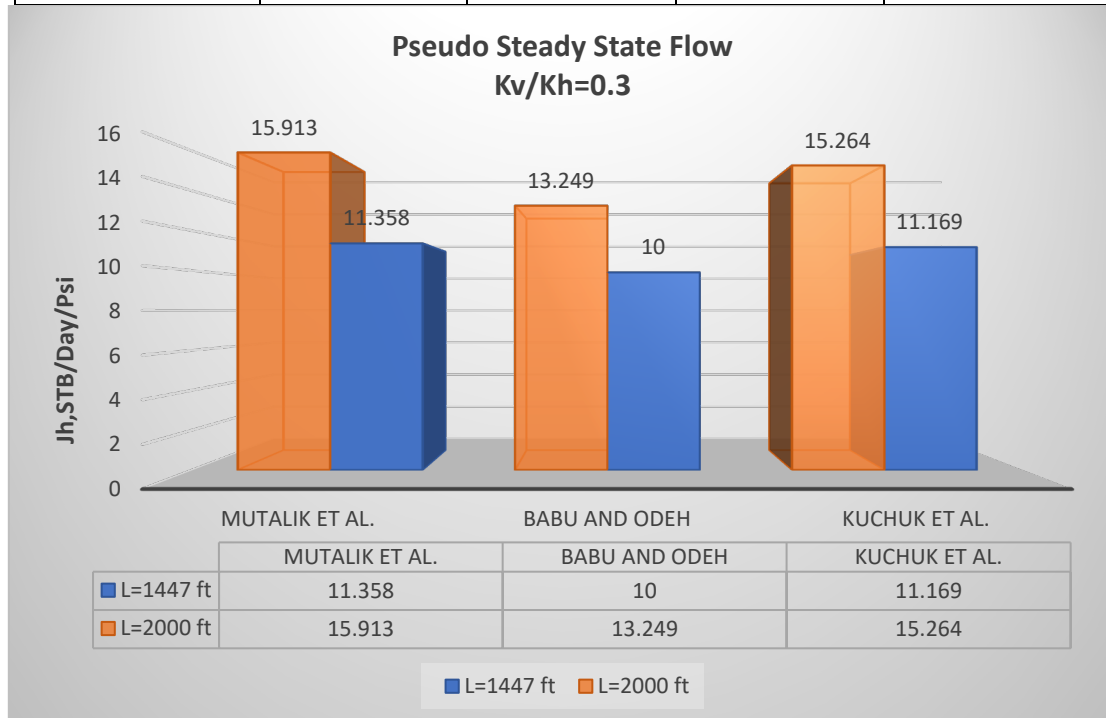


Figure 11. A comparison of horizontal Pseudo Steady State anisotropic Productivity of well (A46).

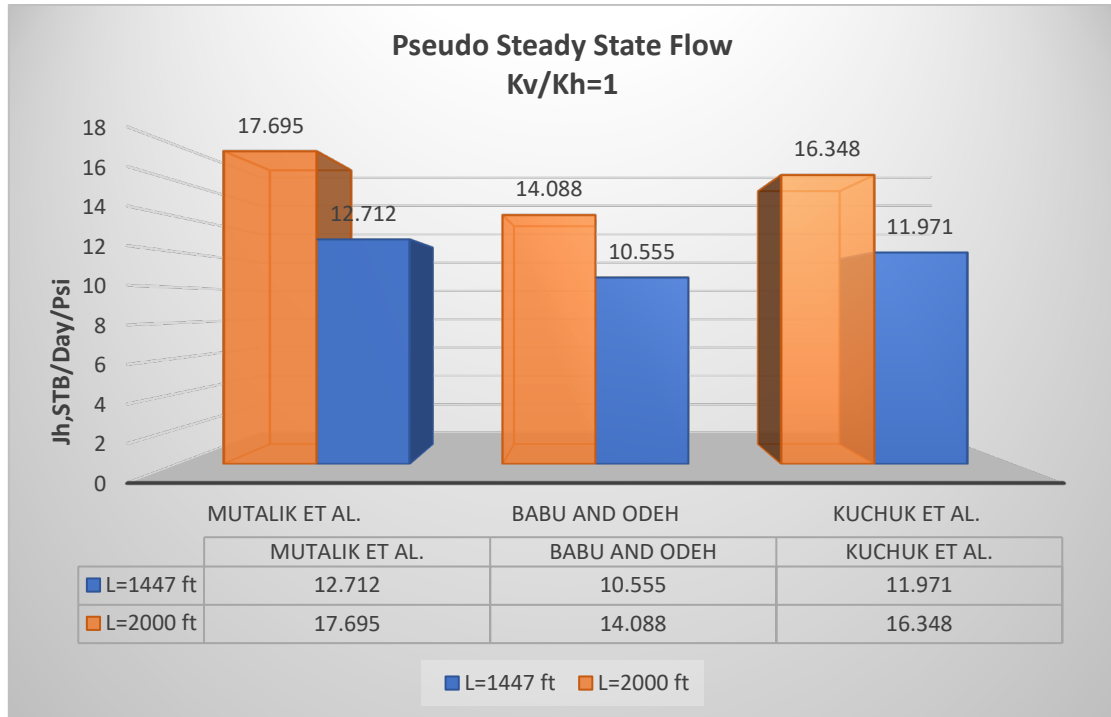


Figure 12. A comparison of horizontal Pseudo Steady State isotropic Productivity of well (A46).

4.2 Steady-State Productivity of well (A 87):

Table 16. A comparison of horizontal well productivities by the four methods for different values of (K_v / K_h)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	$k_v/k_h = 0.3$		$k_v/k_h = 1$	
	L=1234 ft	L=2500 ft	L=1234 ft	L=2500 ft
Brisov	xxx	xxx	4.450	7.399
Giger	6.493	14.458	4.525	8.553
Renard and Dupuy	4.308	7.162	4.449	7.353
Joshi	4.392	7.275	4.412	7.309

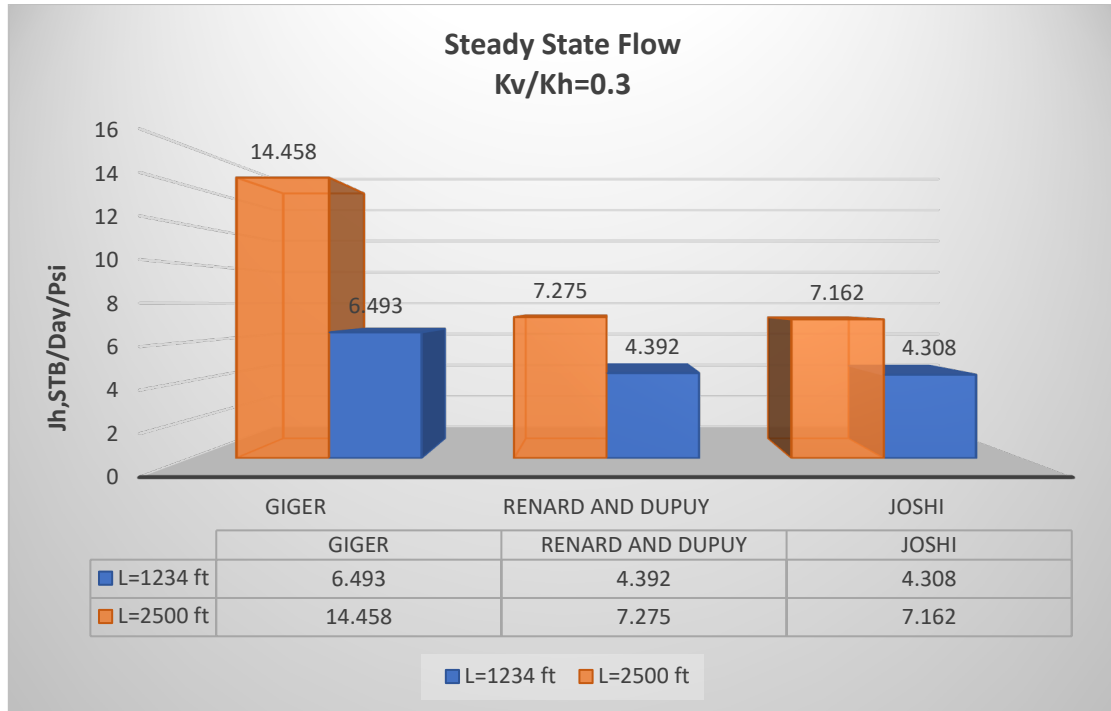


Figure 13. A comparison of horizontal Steady-State anisotropic Productivity of well (A 87).

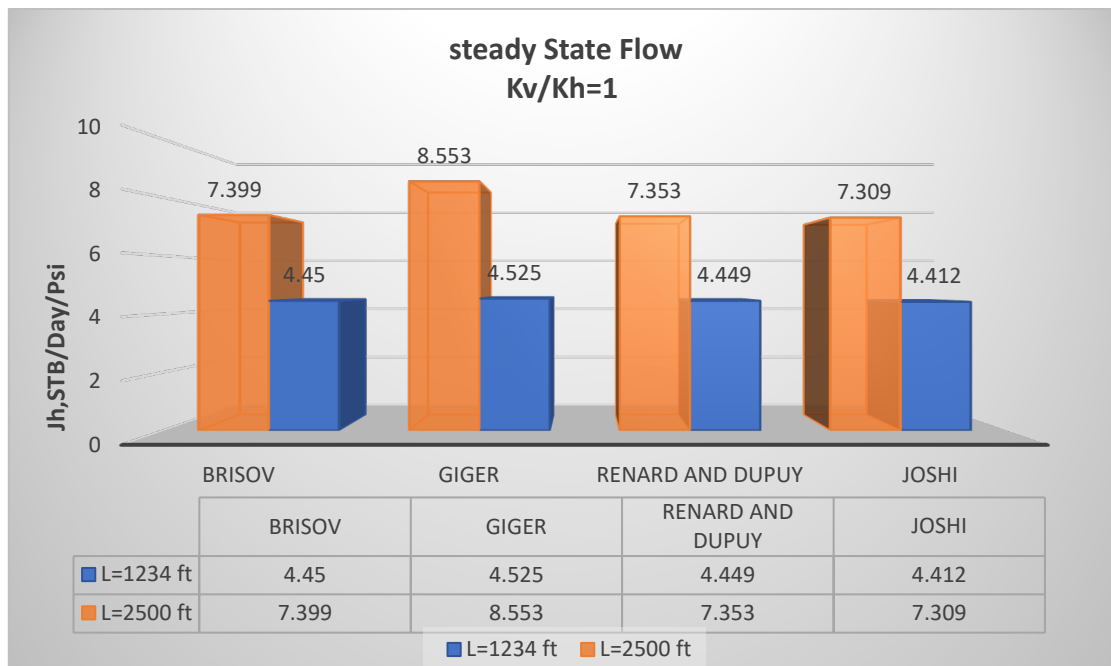


Figure 14. A comparison of horizontal Steady-State isotropic Productivity of well (A 87).

4.3 Pseudo Steady State Productivity of well (A87):

Table 17. A comparison of horizontal well productivity by the three methods for different values of (K_v / K_h)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	$k_v/k_h = 0.3$		$k_v/k_h = 1$	
	L=1234 ft	L=2500 ft	L=1234 ft	L=2500 ft
Mutalik et al.	6.838	13.468	7.025	13.491

Babu and Odeh	5.628	10.748	5.726	10.961
Kuchuk et al.	6.380	12.262	6.501	12.483

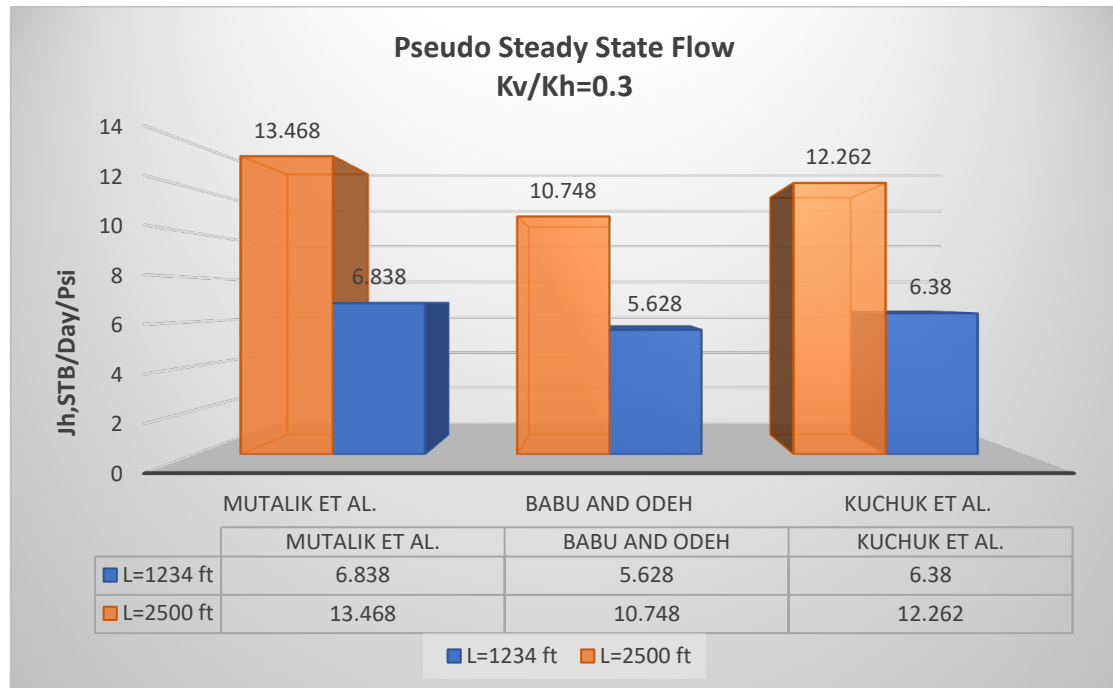


Figure 15. A comparison of horizontal Pseudo Steady State anisotropic Productivity of well (A87).

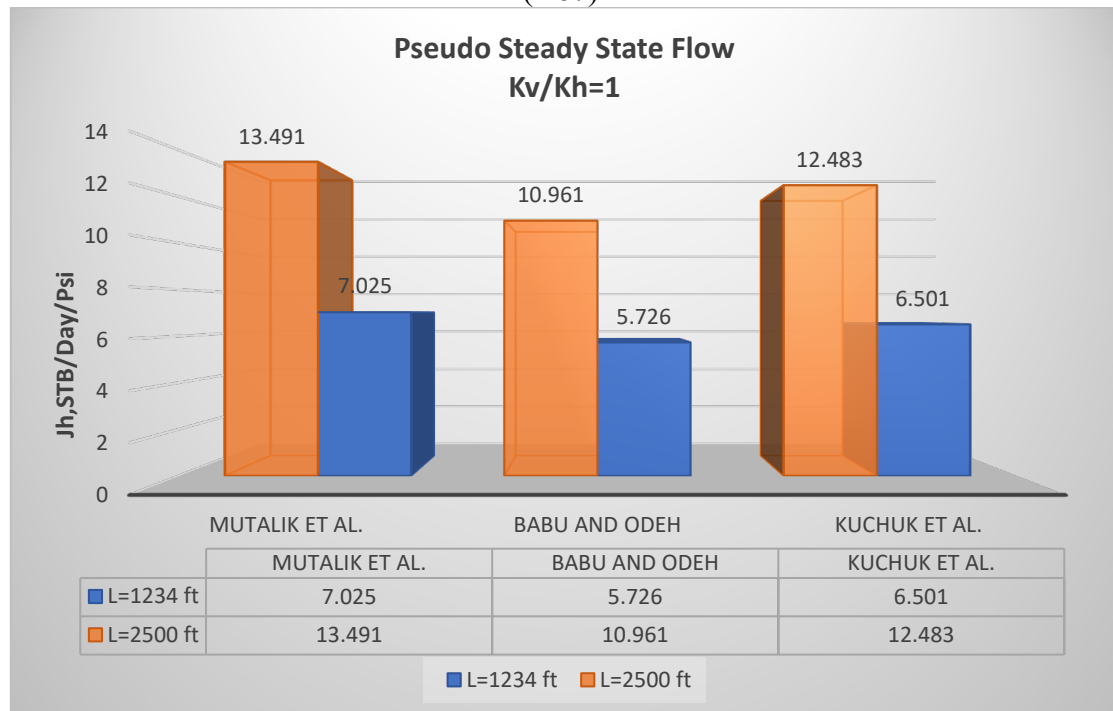


Figure 16. A comparison of horizontal Pseudo Steady State isotropic Productivity of well (A87).

4.4 Steady-State Productivity of well (A 107):

Table 18. A comparison of horizontal well productivities by the four methods for different values of (Kv / Kh)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	kv/kh = 0.3		kv/kh = 1	
	L=1741 ft	L=2500 ft	L=1741 ft	L=2500 ft
Brisov	xxx	xxx	8.202	11.010
Giger	10.770	16.728	8.556	12.654
Renard and Dupuy	7.805	10.461	8.193	10.945
Joshi	7.474	10.046	8.036	10.749

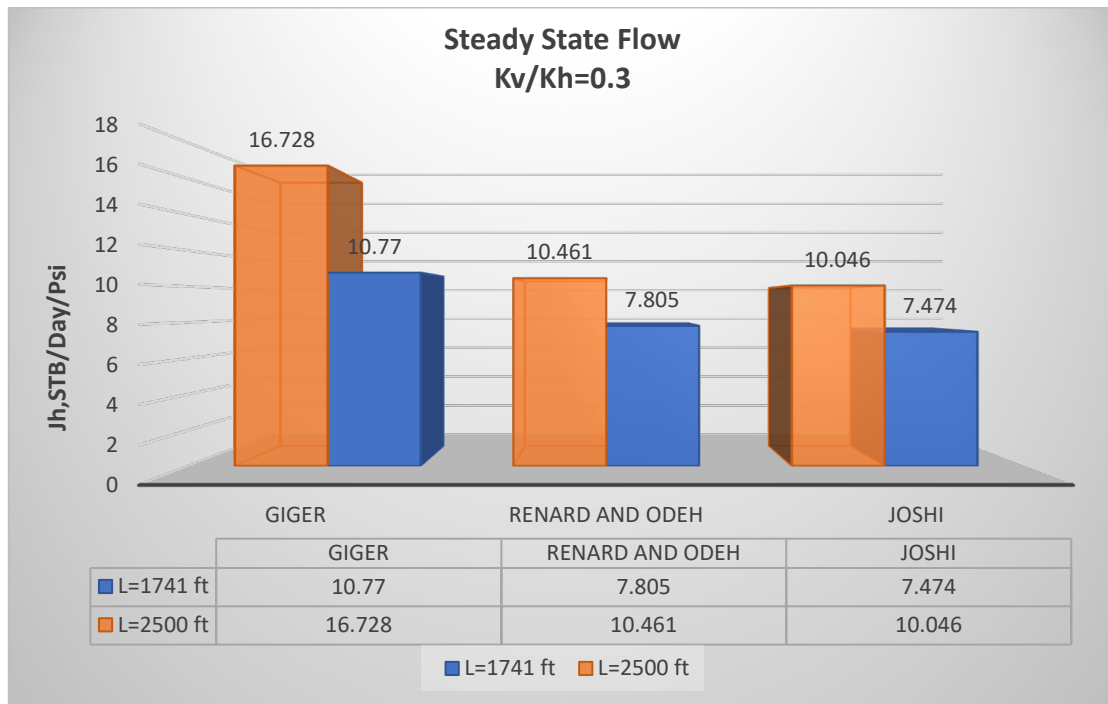


Figure 17. A comparison of horizontal Steady-State anisotropic Productivity of well (A 107).

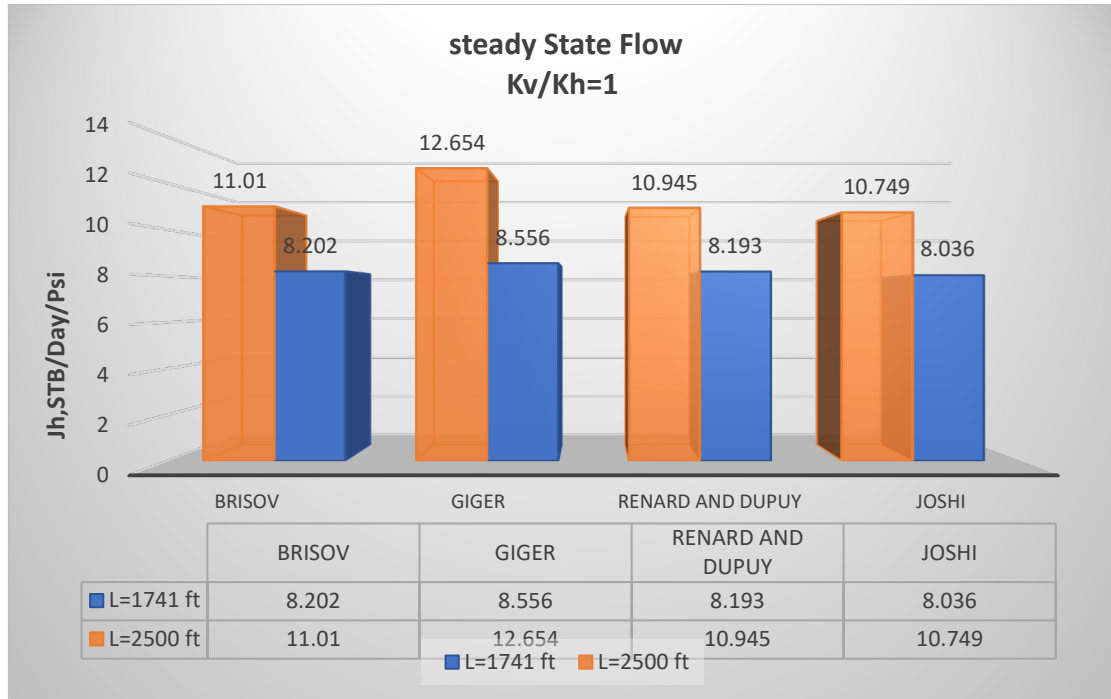


Figure 18. A comparison of horizontal Steady-State isotropic Productivity of well (A 107).

4.5 Pseudo Steady State Productivity of well (A107):

Table 19. A comparison of horizontal well productivity by the three methods for different values of (Kv / Kh)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	kv/kh = 0.3		kv/kh = 1	
	L=1741 ft	L=2500 ft	L=1741 ft	L=2500 ft
Mutalik et al.	12.529	20.321	13.877	22.748
Babu and Odeh	10.337	14.935	11.049	16.222
Kuchuk et al.	11.702	16.824	12.592	18.107

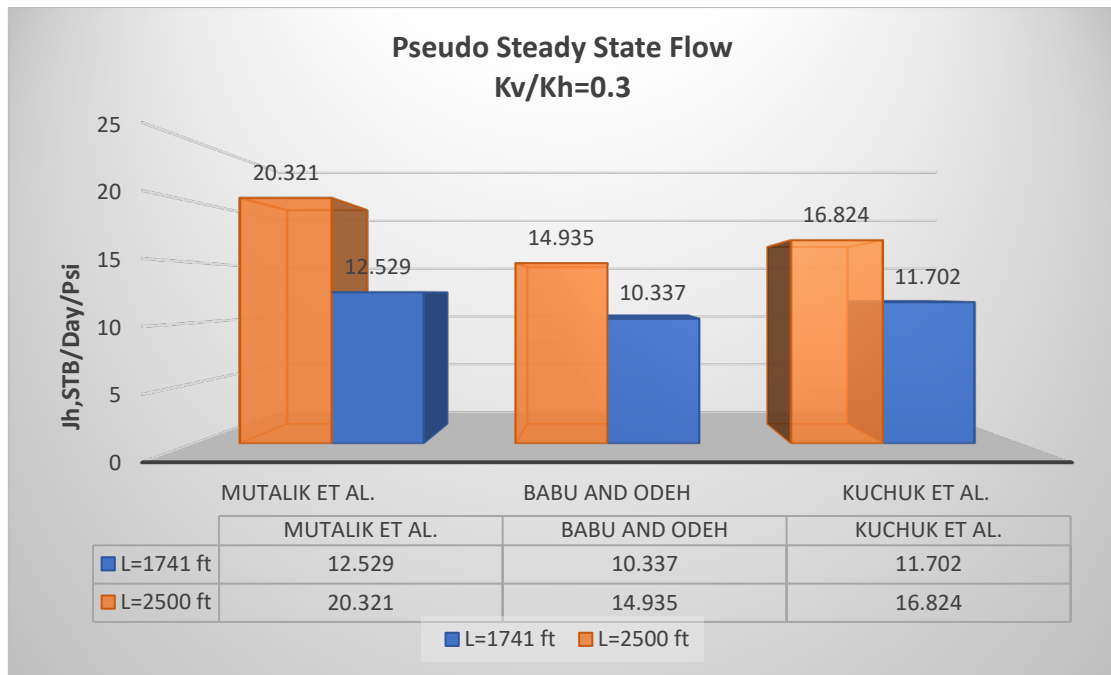


Figure 19. A comparison of horizontal Pseudo Steady State anisotropic Productivity of well (A107).

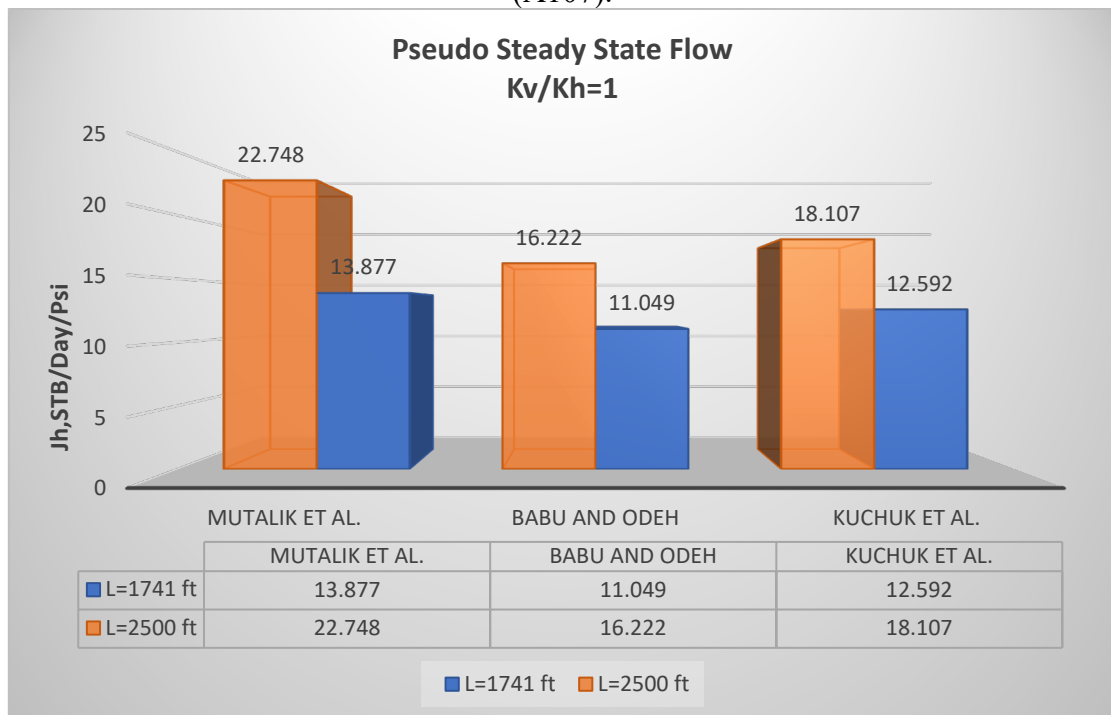


Figure 20. A comparison of horizontal Pseudo Steady State isotropic Productivity of well (A107).

4.6 Steady-State Productivity of well (A65):

Table 20. A comparison of horizontal well productivities by the four methods for different values of (K_v / K_h)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	kv/kh = 0.3		kv/kh = 1	
	L=1994 ft	L=2500 ft	L=1994 ft	L=2500 ft

Brisov	xxx	xxx	2.143	2.599
Giger	3.123	4.181	2.287	2.992
Renard and Dupuy	2.060	2.492	2.139	2.583
Joshi	1.983	2.402	2.103	2.542

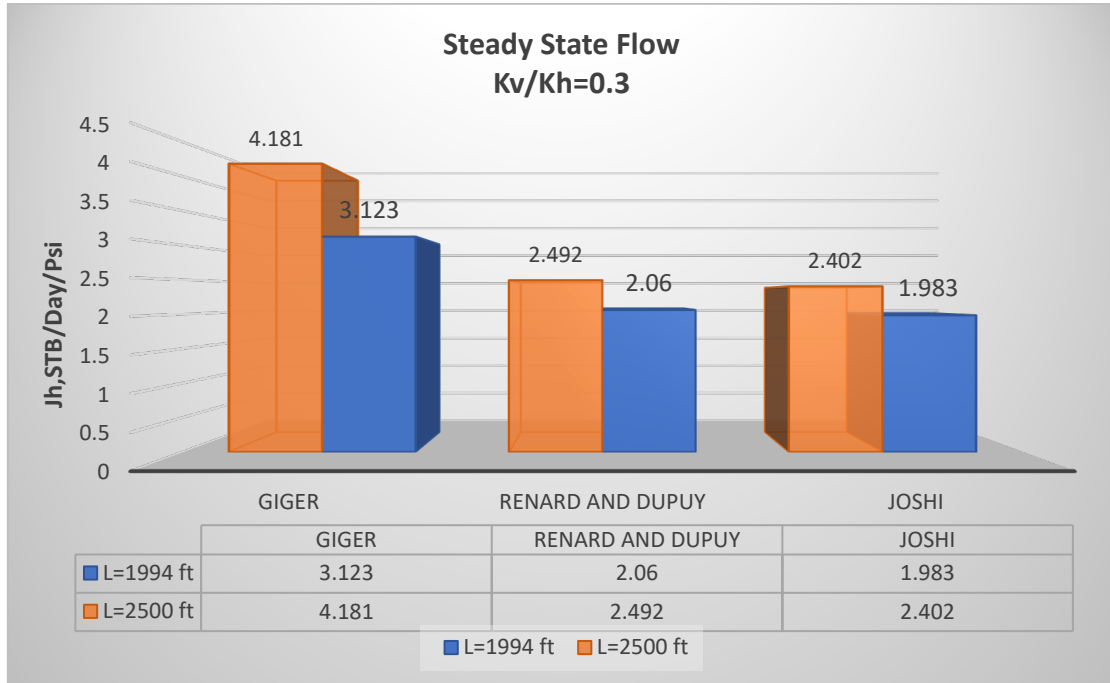


Figure 21. A comparison of horizontal Steady-State anisotropic Productivity of well (A 65).

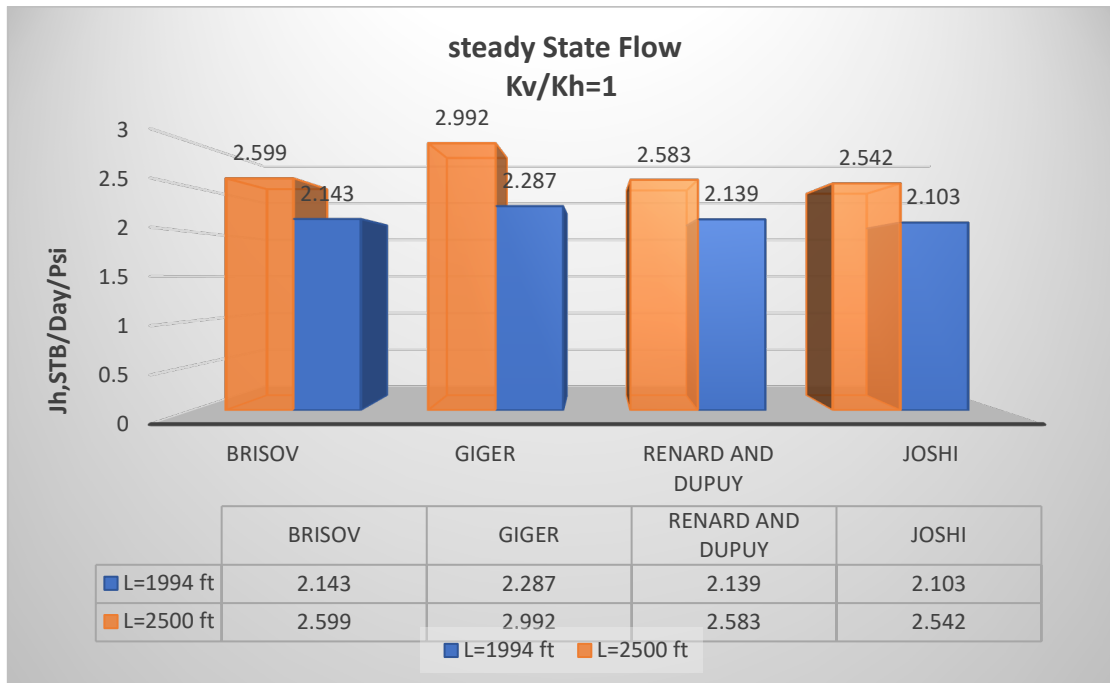


Figure 22. A comparison of horizontal Steady-State isotropic Productivity of well (A 65).

4.7 Pseudo Steady State Productivity of well (A65):

Table 21. A comparison of horizontal well productivity by the three methods for different values of (Kv/ Kh)

Horizontal well productivity index (J_h) STB/day/psi				
Methods	kv/kh = 0.3		kv/kh = 1	
	L=1994 ft	L=2500 ft	L=1994 ft	L=2500 ft
Mutalik et al.	3.398	4.157	3.737	4.521
Babu and Odeh	2.824	3.589	2.979	3.789
Kuchuk et al.	3.264	4.057	3.465	4.305

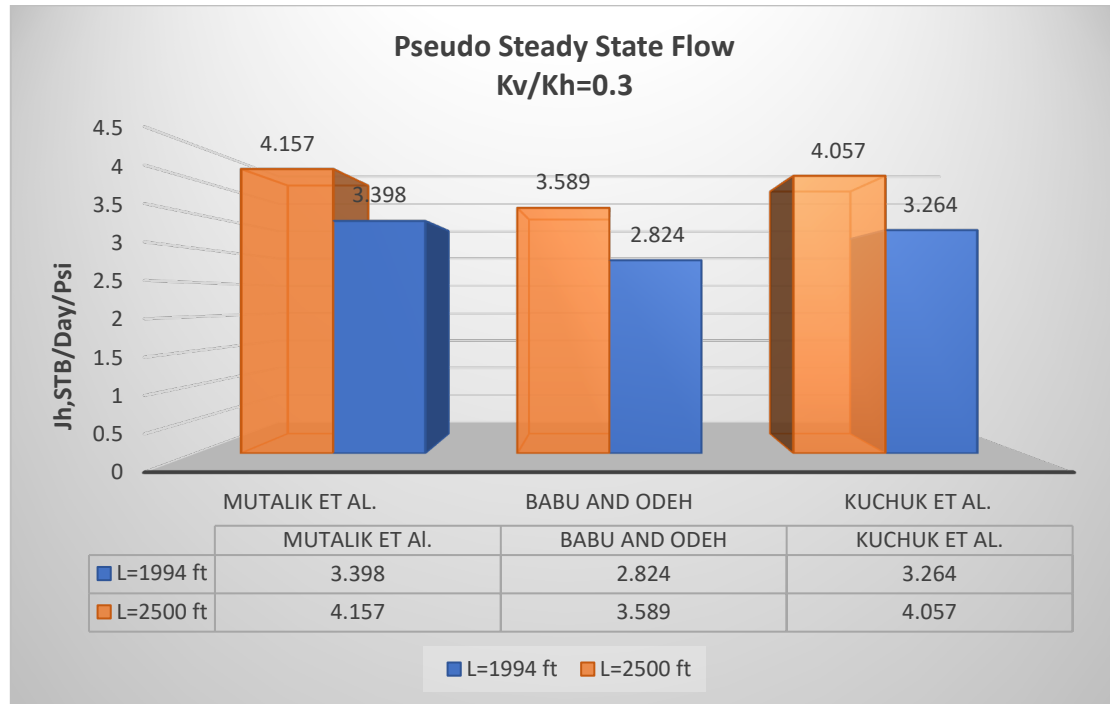


Figure 23. A comparison of horizontal Pseudo Steady State anisotropic Productivity of well (A65).

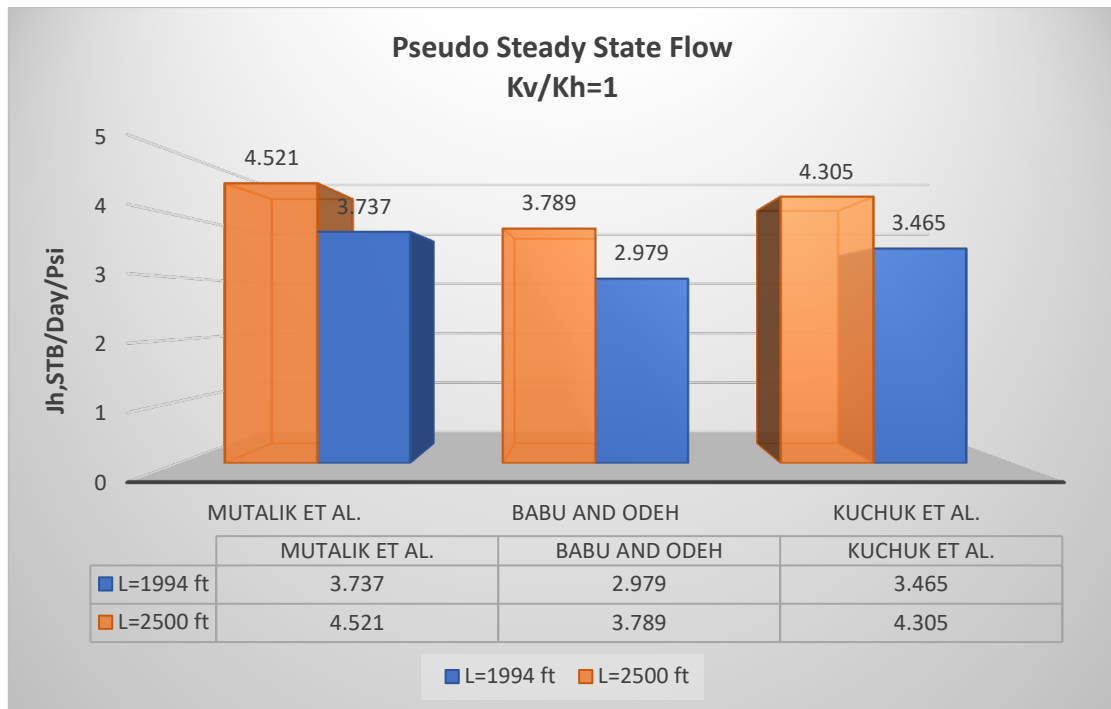


Figure 24. A comparison of horizontal Pseudo Steady State isotropic Productivity of well (A65).

Table 22. A comparison between horizontal and vertical productivities by the four methods at ($K_v / K_h = 1$) for well (A46)

Methods	Horizontal well, J_h	Vertical well, J_v
Brisov	8.087	1.751
Giger	8.291	1.751
Renard and Dupuy	8.083	1.751
Joshi	7.917	1.751

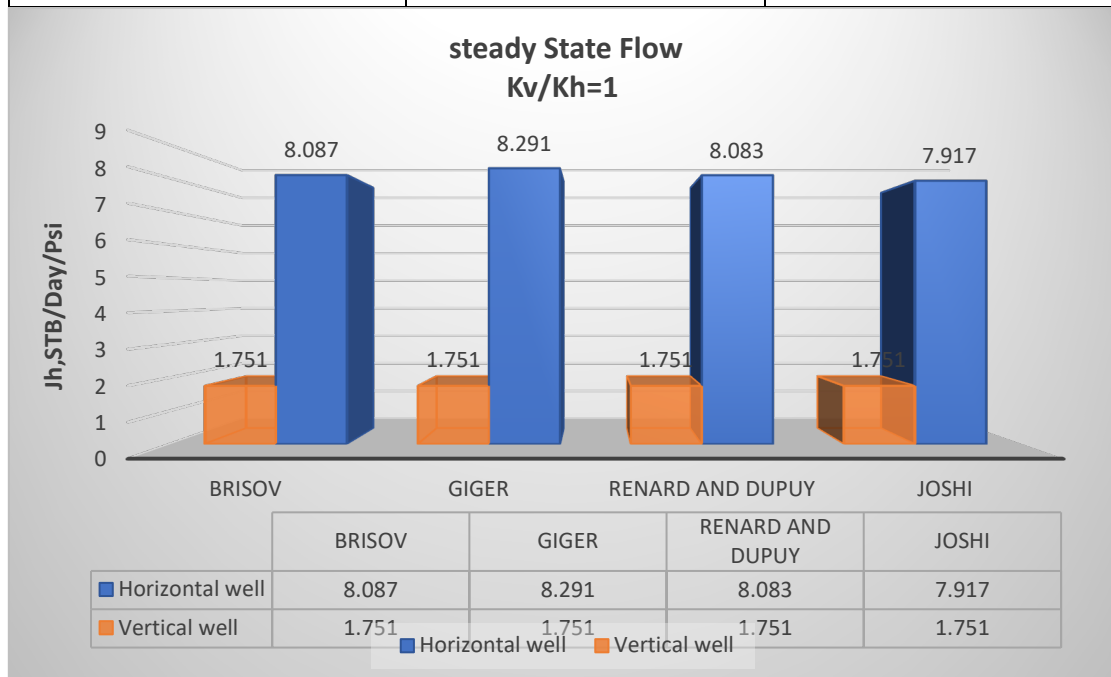


Figure 25. A comparison of horizontal and vertical productivities at ($K_v / K_h = 1$) for well (A46).

Table 23. A comparison between horizontal and vertical productivities by the four methods at ($K_v / K_h = 1$) for well (A87)

Vertical well, J_v	Horizontal well, J_h	Methods
1.0187	4.450	Brisov
1.0187	4.525	Giger
1.0187	4.449	Renard and Dupuy
1.0187	4.412	Joshi

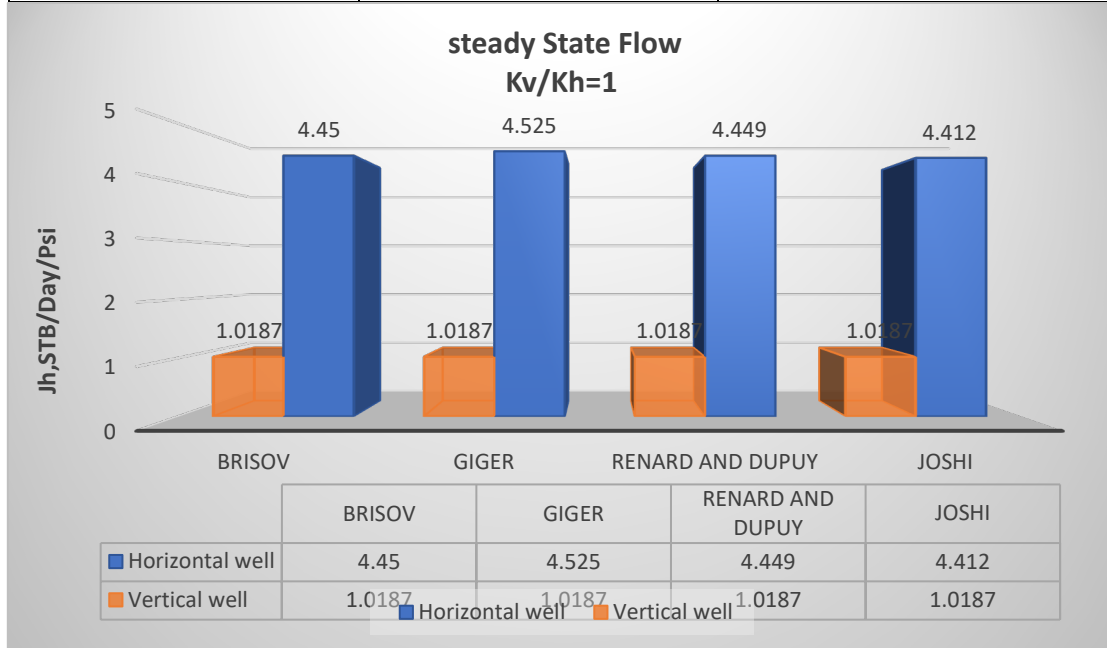


Figure 26. A comparison of horizontal and vertical productivities at ($K_v / K_h = 1$) for well (A87).

Table 24. A comparison between horizontal and vertical productivities by the four methods at ($K_v / K_h = 1$) for well (A107)

Methods	Horizontal well, J_h	Vertical well, J_v
Brisov	8.202	1.520
Giger	8.556	1.520
Renard and Dupuy	8.193	1.520
Joshi	8.036	1.520

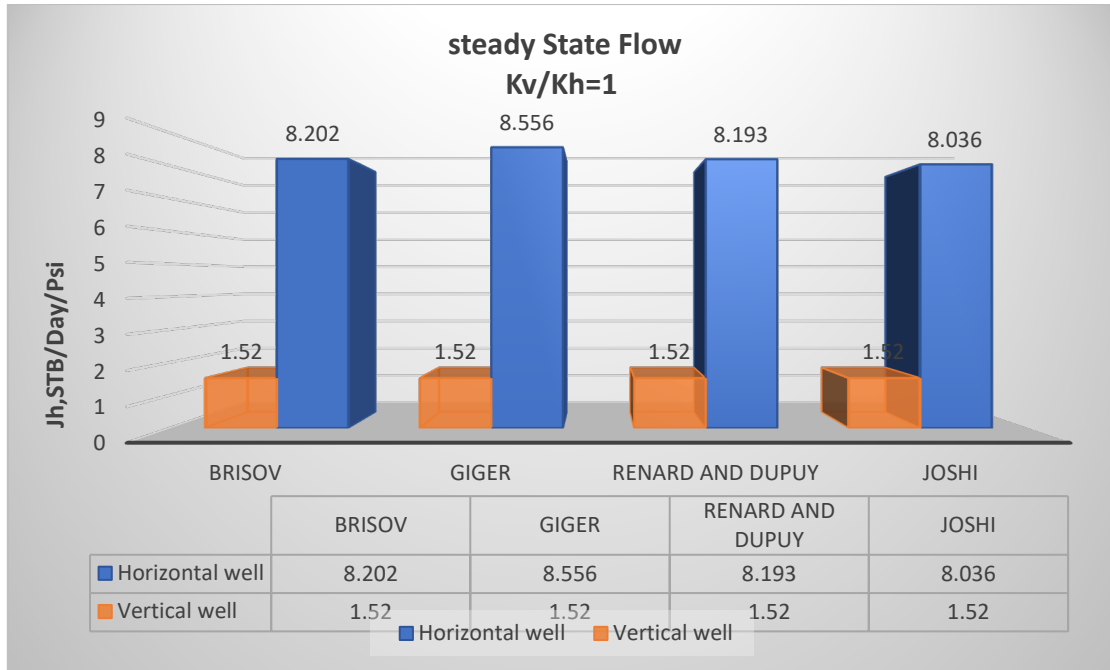


Figure 27. A comparison of horizontal and vertical productivities at ($K_v / K_h = 1$) for well (A107).

Table 25. A comparison between horizontal and vertical productivities by the four methods at ($K_v / K_h = 1$) for well (A65)

Methods	Horizontal well, J_h	Vertical well, J_v
Brisov	2.143	0.368
Giger	2.287	0.368
Renard and Dupuy	2.139	0.368
Joshi	2.103	0.368

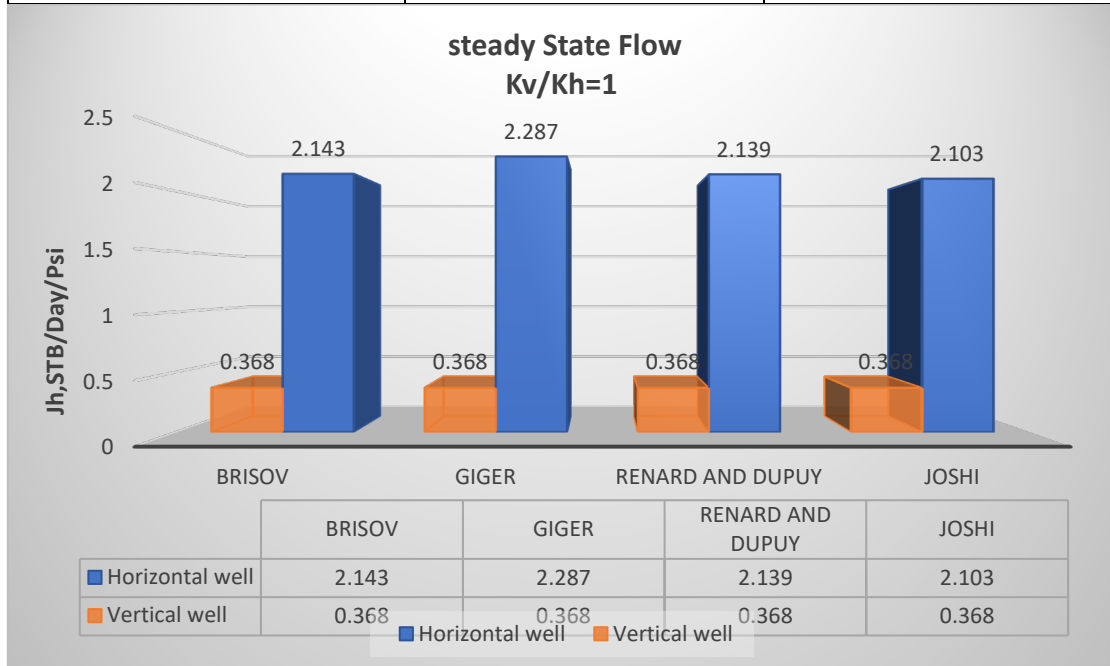


Figure 28. A comparison of horizontal and vertical productivities at ($K_v / K_h = 1$) for well (A65).

Summarized of results:

- **Steady State Isotropic:**

Methods	J_h	J_h / J_v	Actual J_h	Error %
Borisov	8.087	4.619	7.578	6.3
Giger	8.291	4.735	7.578	8.6
Renard	8.083	4.616	7.578	6.2
Joshi	7.918	4.520	7.578	4.3

- **Steady State Anisotropic:**

Methods	J_h	Actual J_h	Error %
Giger	10.123	7.578	25.1
Renard	7.359	7.578	2.9
Joshi	7.708	7.578	1.7

- **Pseudo Steady State Isotropic:**

Methods	J_h	J_h / J_v	Actual J_h	Error %
Mutalik et al	12.712	7.260	7.578	40.4
Babu And Odeh	10.555	6.028	7.578	28.2
Kuchuk et al	11.971	6.837	7.578	36.7

- **Pseudo Steady State Anisotropic:**

Methods	J_h	Actual J_h	Error %
Mutalik et	11.358	7.578	33.3
Babu And Odeh	9.906	7.578	23.5

5.0 Conclusion & Recommendation

5.1 Conclusion

The productivity index was calculated for four horizontal wells at the (west mabruk) oilfield using different methods and techniques. The effect of reservoir formation isotropy and anisotropy on productivity index was also studied. Additionally, Steady state and pseudo-steady were presented and compared for several calculation methods.

The following conclusions were obtained based on this study:

- It very important to determine whether the reservoir is isotropic or anisotropic as that appears directly affect productivity index of the wells. Assuming anisotropic reservoirs will undervalue the productivity index results that leads to misjudge the well's potential for production.
- Specific methods, that we used, presented a very close productivity index values to the actual values that were estimated by the Mabruk Oil Company. Thus, these methods can be used to estimate productivity index in future
- Productivity in horizontal wells does not only depends on well length, also on the type of completion used, well location, vertical permeability, drainage area, fluid viscosity and perforation percentage, and reservoir size. However, it is a strong function of pay zone

thickness, the permeability perpendicular to the well in the horizontal plane. Also For maximum productivity, the horizontal well should be located at mid-height of the pay zone.

- Our results shows that there are many factors effecting the evaluation of productivity index in horizontal wells (e.g. the length of horizontal section, the ratio between vertical to horizontal permeability, drainage radius of horizontal section or drainage area of horizontal well, and mechanical skin factor)
- Comparing between all methods in steady-state flow regimes at isotropic and anisotropic.
- Comparing between all methods in pseudo steady state flow regimes at isotropic anisotropic.
- Comparing for each well the productivity index for horizontal well to vertical well according this comparing the horizontal productivity value is so much greater than vertical productivity value, the horizontal wells the productivity increase (3-5) times, compared with vertical wells.
- Use the horizontal drilling can be avoids many problems, like water coning or others problems and to reduce number of wells drilled in the field.
- Any table and figure in this project was, created for this tables and figures (**Numerical Analysis Equations**) to make more accurate and faster reliable results comparing to the results from table and figures.

5.2 Recommendations

- In future work, we recommend deriving productivity index from core analysis data and recent well testing for higher accuracy. Then compare results to analytical methods and finally determine which methods work better to represent the reservoir.
- We recommend in future work the horizontal well high recovery factor because it have greater productivity index comparing to vertical well.
- We recommend in future work the drilling horizontal section the drilling deeper will increase the value of productivity index of the well, this leads to increase the recovery factor and production and this mean more profit.

6.0 Nomenclaturfs

q = Flow rate, emisec.

P_{wf} = Flowing wellbore pressure, psi.

K- Permeability, Darcy.

A- Cross-sectional area of tlow, em?

μ = Viscosity, ep.

ΔP = Pressure drap, atmospheres.

Δx = Distance, cm

J_h = Produstivity index of a horiznotal well, STB/day/psi.

q_h = Oil fow rate of a horizontal well, **STB** day.

k_h = Horizontal permeability, me.

h = Keservoir thickness, ft

ΔP = Pressure drop from the drainage radius to the wellbore, pai.

μ_0 = Oil viscosity, cp.

B_0 = Oil formatian volume factor, RB/STB.

T_F & r_{zh} = Drainage radius of vertical and horizontal wells, respectively, ft.

L = Horizontal well leneth, ft.

r_w = Wellhore radias, f_t

r'_u = Efloctive wellibore radius, ft.

a = Half the major axis of drainage ellipse, f .
 k_y = Vertical permeability, md.
 \emptyset = Porosity, fraction (%).
 A = Drainage area, acres.
 x, y, z = Cartesian coordinates.
 k_{ert} = Effective reservoir permeability, md.
 B = Parameter used in integration.
 L_{fr} = Dimensionless well length.
 r_n = Equivalent drainage radius, fr.
 S_{in} = Mechanical skin factor, dimensionless.
 S_{CA} = Shape-related skin factor.
 C^2 = Shape factor conversion constant.
 D = Non-darcy flow coefficient.
 k_y = The horizontal permeability in the direction perpendicular to the wellbore, md
 A_1 = Horizontal well drainage area in the vertical plane, ft^2
 C_H = Shape factor.
 S_g = Skin factor due to partial penetration of the horizontal well in the areal plane
 y_u = The distance from the horizontal well to the closest boundary in the (y) direction, ft
 $2w$ = The vertical distance between the horizontal well and the bottom boundary, ft.
 PXY = Results from the degree of penetration in the $x - y^{-2}$, plane.
 PXY' = Results from the location of the well in $x - y$ plane.
 y_1 = Coordinate of beginning of well, ft.
 x_w = The distance from the horizontal well mid-point to the closest boundary in the (x) direction, ft.
 y_2 = Coordinate of end of well, ft.
 PY = Results from the degree of penetration in the y plane.
 Md y_w = The distance from the horizontal well mid-point to the closest boundary in the (y) direction, ft.
 F = Dimensionless function

7.0 Abbreviation

Cm - Centimeter.
Cm³ - Cubic centimeter.
Sec - Second.
Cp - Centipoises.
Ft - Feet.
RB - Reservoir barrel.
STB - Stock tank barrel.
Psi - Pound per square inch.

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