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A Regression Analysis Approach to Van Everdingen-Hurst Dimensionless Water Influx Variables for Infinite and Finite Aquifers

Muhammad Taufiq Fathaddin[1], Yarra Sutadiwiria[1], Taufan Marhaendrajana[2], Sonny Irawan[3]
Onnie Ridaliani Prapansya[1], and Asri Nugrahanti[1]

[1]Universitas Trisakti
Kyai Tapa Street, Jakarta, Indonesia

[2]Institut Teknologi Bandung
Ganesa Street, Bandung, Indonesia

[3]Nazarbayev University
Kabanbay batyr Ave., Astana, Kazakhstan

Corresponding author: msuweleh@gmail.com

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ABSTRACT - Water influx calculations have relied on accurate values of the Van Everdingen-Hurst WeD dimensionless variables. For programming and hand calculators, equations are needed to determine WeD. Previous models provide equations for WeD calculations for infinite aquifer cases. This paper presents two sets of regression equations that are simple to apply to obtain accurate values of WeD for either infinite or finite aquifer cases. The proposed equations have good agreement with the Van Everdingen-Hurst method with an average difference of 0.77% and 1.18% for the cases of infinite aquifer and finite aquifer, respectively.

Keywords: water influx, reservoir, aquifer, infinite, finite.

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INTRODUCTION

In the development of oil and gas field, reservoir characterisation is a crucial step. It occurs during the evaluation stage of either a green field or a brown field, during which further development choices are considered. This allows petroleum engineers to have a better understanding of the reservoir and its properties (Butarbutar et al., 2023). As a result, several models have been created to depict the reservoir and forecast how the reservoir will perform in various scenarios (Sam-Marcus et al., 2018). Water inflow is an important parameter used in reservoir characterization. This parameter is possessed by water-drive reservoirs. Water influx plays a significant role in reservoir performance because it affects such properties as water saturation, capillary pressure, and relative permeability. In addition, it contributes to the fluid movement and distribution in the reservoir. Water that enters the reservoir comes from the aquifer that supports the reservoir pressure. The aquifer reacts to offset or slows down pressure drops resulting from reservoir fluid production

(BinMerdhah et al., 2015; Widarsono, 2019). Water influx is critical to oil recovery improvement in oil reservoirs (Al-Mahasneh, et al., 2023). A comparison of the determination of oil recovery factor for edge and bottom water drive mechanisms using water influx models reveals that aquifer volume and permeability have a linear connection with both bottom and edge water drives. Bottom water drive is more efficient than edge water drive; hence, bottom water drive reservoirs have higher oil recovery than edge water drive reservoirs (Nmegbu et al., 2021). The approximate recovery factor range for water drive oil reservoir is approximately 30 percent of the amount of original oil in place (Rosidelly, 2017).

However, water influx can cause a problem in the water drive gas reservoir. When reservoir fluid is produced, water flows from the aquifer and moves toward the reservoir through the water-gas contact due to a differential pressure. Large volume of gas may be bypassed and left behind the advancing front. Therefore, a considerable portion of the gas can possibly be trapped. As a result, the increased remaining gas reduces the gas recovery from the reservoir (Ogolo, et al., 2014; Al-Mahasneh et al., 2023). A strong water drive reservoir can significantly reduce the recovery factor in the 30 to 85 percent range, where the gas phase is trapped at greater pressures (Roozshenas et al., 2021). Meanwhile, the recovery factor value is usually higher in the case of volumetric gas reservoirs. In many cases, the reservoir volumetric recovery factor ranges between 80 and 90 percent due to the tremendous pressure drop over the life of the reservoir (Abdollahi et al., 2021).

Aquifers are bodies of permeable and porous rock that are saturated with groundwater. Reservoir-aquifer systems are characterized as edge water drive or bottom water drive based on the flow geometry. As oil is produced, water moves into the flanks of an oil reservoir in edge water drive. Bottom water drive occurs in reservoirs with a wide size and a slight dip, when the oil-water contact entirely underlies the oil reservoir (BinMerdhah et al., 2015). Aquifer activity levels are classified as high, moderate, or low. Highly active aquifers exhibit a rapid rise in water cut immediately following the first water breakthrough. Low active aquifers do not respond as quickly to reservoir fluid changes as active water-driven aquifers. This behaviour can be caused by low permeability, heterogeneity, and perhaps other aquifer restrictions. If the aquifer is weak, it will not react rapidly to hydrocarbon depletion, causing the pressure drop to be greater and the water front to be delayed in moving towards the hydrocarbon zone (Roozshenas et al., 2021).

Aquifer modelling is critical for predicting reservoir performance in the future. Characterization of aquifers is necessary for aquifer modelling. However, characterization is a difficult task. This is due to the uncertainty in most aquifer parameters such as aquifer size, permeability, porosity, and water encroachment angle. There is significant uncertainty for a variety of reasons. First, we rarely drill wells into aquifers to learn about the reservoir features of the aquifers. Second, qualities are commonly inferred from what is observed in the reservoir, and finally, the geometry and areal continuity of the aquifers per se are a major concern (Al-Mahasneh et al., 2023; Nmegbu et al., 2021; Terry et al., 2015).

Several models for calculating water influx have been created, all of which are based on assumptions about the features of aquifers. Due to the inherent uncertainties in aquifer characteristics, all the proposed models require historical reservoir performance data to evaluate the constants that represent aquifer property parameters, which are rarely known, with sufficient accuracy from exploration-development drilling for direct applications. The material balance equation can be used to calculate historical water influx if the initial oil-in-place is known by using pore volume calculations (Arwini & Abbassi, 2020). These models are applicable to many flow regimes such as unsteady-state (Fetkovich, 1971; Van Everdingen & Hurst, 1949), pseudo-steady-state (Hurst, 1943), steady-state, and modified steady-state (Schilthuis, 1936).

Okon and Ansa (2021) introduced artificial neural network (ANN) models to predict the reservoir-aquifer variables W_{eD} and P_D that were developed based on the Van Everdingen–Hurst datasets for edge- and bottom-water finite and infinite aquifers (Okon & Ansa, 2021).

In this paper, the Van Everdingen-Hurst method is modified by proposing equations for determining dimensionless water influx (W_{eD}) for both infinite and finite aquifers. Validation is carried out by comparing water influx estimation using this method and previous methods.

Water-Influx Model

An unsteady state model was proposed by Van Everdingen and Hurst. This is the most widely used water-influx model. Their model is a mathematical model that uses the superposition principle to estimate the cumulative water influx in the reservoir. Their model is a Laplace transformation solution to the radial diffusivity problem. As a result, it provides an accurate estimate of water encroachment for nearly all flow regimes, assuming that the flow geometry is radial. Van Everdingen and Hurst solutions are for both constant-terminal-rate and constant-terminal-pressure cases of infinite and finite aquifers. The model can be used for an edge water-drive system, a bottom water-drive system, or a linear water-drive system (Ahmed, 2019; Klins, et al., 1988; Van Everdingen & Hurst, 1949).

Van Everdingen and Hurst characterized their mathematical relationship for calculating water influx as dimensionless water influx W_{eD}. The dimensionless water influx is a function of the dimensionless time t_D and dimensionless radius r_D. The water influx (W_e) is (BinMerdhah et al., 2015; Edwardson et al., 1962; Okon & Ansa, 2021):

$$W_e = B \Delta p W_{eD} \quad (1)$$

Water influx constant (B) and dimensionless angle (f) are defined as:

$$B = 1.119 \phi c_t r_e^2 h f \quad (2)$$

and

$$f = \frac{\theta}{360} \quad (3)$$

where:

B	= water influx constant, bbl/psi
c_t	= total compressibility, psi^{-1}
f	= dimensionless angle
h	= aquifer thickness, ft
p	= pressure, psi
Δp	= pressure drop at the boundary, psi
r_e	= reservoir radius, ft
t_D	= dimensionless time
W_e	= cumulative water influx, bbl
W_{eD}	= dimensionless water influx
ϕ	= porosity, fraction

Edwardson et al. (1962) introduced three sets of equations for computing the dimensionless water influx WeD for infinite aquifers. The equations are as follows (Ahmed & McKinney 2005; Edwardson et al., 1962).

For $t_D < 0.01$

$$W_{eD} = 2\left(\frac{t_D}{\pi}\right)^{0.5} \quad (4)$$

For $0.01 < t_D < 200$

$$W_{eD} = \frac{1.2838\sqrt{t_D} + 1.19328 t_D}{1 + 0.616599\sqrt{t_D} + 0.0413008 t_D} + \frac{0.269872 (t_D)^{3/2} + 0.00855294 (t_D)^2}{1 + 0.616599\sqrt{t_D} + 0.0413008 t_D} \quad (5)$$

For $t_D > 200$

$$W_{eD} = \frac{-4.2881 + 2.02566 t_D}{\ln(t_D)} \quad (6)$$

METHODOLOGY

This research includes collecting data from references for modelling and validation. Statistical parameters are used to evaluate the proposed model.

Data Acquisition and Preparation for Modeling

The proposed equations were derived using a regression analysis based on the data from Van Everdingen-Hurst's (1949) dimensionless water influx (Van Everdingen & Hurst, 1949). Dimensionless datasets of time (t_D), radius (r_{eD}), and water influx (W_{eD}) required for finite (bounded) and infinite aquifers were extracted from Ahmed (2019) and Ahmed-McKinney (2005). The dimensionless datasets are based on an analytical solution (using Laplace transformation) to the radial diffusivity equation, assuming there is a step change between the reservoir and the aquifer pressure. The dimensionless water influx (W_{eD}) is as a function of dimensionless radius (r_{eD}) and dimensionless datasets of time (t_D) (Ahmed 2019; Ahmed and McKinney 2005).

Data Acquisition and Preparation for Validation

The data on Hummar reservoir for the validation of infinite aquifer cases was obtained from Al-Mahasneh et al. (2023). The reservoir is formed in the Azraq Basin located in northeastern Jordan (Al-Mahasneh et al., 2023). Data on Hummar reservoir for infinite reservoir cases are given in Tables 1 and 2. The data consists of several parameters including reservoir radius, aquifer thickness, aquifer permeability, aquifer porosity, water viscosity, water and rock compressibility, and pressure at reservoir-aquifer boundary as a function of time.

Table 1
The properties of reservoir and aquifer for infinite aquifer cases

Parameter	Value
Reservoir radius r_e, ft	6514.8
Aquifer thickness h, ft	16.7
Aquifer permeability k, mD	132
Aquifer porosity ϕ, fraction	0.11
Water viscosity μ_w, cP	0.3
Water compressibility c_w, psi^{-1}	3.07E-06
Aquifer rock compressibility c_f, psi^{-1}	2.35E-06

Table 2
History of reservoir pressure for infinite aquifer cases

Time t, days	Pressure p, psi
0	3934.74
100	3882.38
117	3877.45
404	3870.63
660	3868.60

The data for validating finite aquifer cases was a hypothetical reservoir obtained from Fetkovich (Fetkovich, 1971). The additional data required for finite aquifer cases was the ratio of the aquifer and reservoir radii. The properties of the reservoir and aquifer used are listed in Tables 3 and 4.

Evaluation Method

Validation was carried out by comparing the cumulative water influx predictions from the proposed equations and the original Van Everdingen-Hurst method. In addition, comparisons were also made with the equations of Edwardson et al. To evaluate the prediction accuracy of the proposed equation, the statistical parameter used was the mean absolute relative error (MARE). MARE is defined as follows (Fathaddin et al., 2023):

$$MARE = \frac{1}{n}\sum_{i-1}^{n}\left|\frac{x_i - x_i'}{x_i}\right| \times 100\% \quad (7)$$

Where n is the amount of data, x_i and x_i' are the prediction of Van Everdingen-Hurst and that of the proposed equations, respectively.

Table 3
The properties of reservoir, aquifer, and fluid for finite aquifer cases

Parameter	Value
Reservoir radius r_e, ft	10,000
Ratio of aquifer to reservoir radii r_a/r_e, fraction	10
Aquifer thickness h, ft	100
Aquifer permeability k, mD	100
Aquifer porosity ϕ, fraction	0.2
Water viscosity μ_w, cP	0.5
Water compressibility c_w, psi^{-1}	3.00E-06
Aquifer rock compressibility c_f, psi^{-1}	3.00E-06

Table 4
History of reservoir pressure for finite aquifer cases

Time t, days	Pressure p, psi
0	2000
1825	1658.94
3650	1350.99
5475	1009.93
7300	678.808

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RESULT AND DISCUSSION

Van Everdingen and Hurst (vE-H) provide dimensionless water influx (W_{eD}) values in the form of graphs and tables for infinite aquifers and for finite aquifers with different variations in the ratio of the radius of the aquifer (r_a) to the reservoir (r_e). In this study, the W_{eD} value for an aquifer with infinite outer boundaries is estimated using the following equation:

$$W_{eD} = At_D^B \tag{8}$$

The constants A and B are obtained using a regression analysis. The constants for various dimensionless time intervals (t_D) are given in Table 5.

Table 5
Constants A and B for determination of infinite aquifer W_{eD}

Interval	A	B
$t_D \leq 1$	1.532787	0.571654
$1 < t_D \leq 10$	1.541028	0.676410
$10 < t_D \leq 100$	1.239466	0.768089
$100 < t_D \leq 1000$	0.915613	0.834147
$1000 < t_D \leq$ 1E+04	0.684906	0.876378
1E+04 $< t_D \leq$ 1E+05	0.538558	0.902510
1E+05 $< t_D \leq$ 1E+06	0.436972	0.920611
1E+06 $< t_D \leq$ 1E+07	0.365947	0.933385
1E+07 $< t_D \leq$ 1E+08	0.315943	0.942423
1E+08 $< t_D \leq$ 1E+09	0.279469	0.949029
1E+09 $< t_D \leq$ 1E+10	0.250020	0.954365
$t_D >$1E+10	0.243619	0.955614

As is the case of infinite aquifer boundaries, for the case where the outer boundary of the aquifer is finite, the determination of the dimensionless water influx (W_{eD}) equations is derived from the polynomial regression analysis method. SPSS software is used to find the most appropriate equation for each dimensionless time interval and ratio of aquifer to reservoir radii (r_a/r_e) as given in Table 6. The r_a/r_e ratio varies from 1.5 to 10.

The validation results of the proposed equations for infinite aquifer cases are shown in Table 7. The table shows that the cumulative water influx estimates of the proposed equations provide a good agreement with the Van Everdingen-Hurst method. The percentage difference of water influx estimated using the proposed equations of the Van Everdingen-Hurst method ranges from 0.15% to 1.53%. In addition, the table shows that the cumulative water influx estimates with the proposed equations are more accurate than the equations of Edwardson et al. The MARE values for the proposed equations and the equations of Edwardson et al. (1962) are 0.77% and 1.20%, respectively.

Table 6
Equations for estimating finite aquifer W_{eD}

r_a/r_e	Interval	Equation
1.5	$t_D \leq 0.8$	W_{eD} = -5.4837E+00(t_D^4) + 1.1898E+01(t_D^3) - 9.5579E+00(t_D^2) + 3.4517E+00(t_D) + 1.3179E-01
	$t_D > 0.8$	W_{eD} = 0.624
2.0	$t_D \leq 5$	W_{eD} = -2.2021E-02(t_D^4) + 2.6280E-01(t_D^3) - 1.0996E+00(t_D^2) + 1.9292E+00(t_D) + 2.4553E-01
	$t_D > 5$	W_{eD} = 1.500
2.5	$t_D \leq 10$	W_{eD} = -1.6782E-03(t_D^4) + 4.2117E-02(t_D^3) - 3.8065E-01(t_D^2) + 1.4971E+00(t_D) + 3.4633E-01
	$t_D > 10$	W_{eD} = 2.624
3.0	$t_D \leq 24$	W_{eD} = -9.9524E-05(t_D^4) + 5.8450E-03(t_D^3) - 1.2149E-01(t_D^2) + 1.0633E+00(t_D) + 5.8577E-01
	$t_D > 24$	W_{eD} = 4.000
3.5	$t_D \leq 40$	W_{eD} = -1.7309E-05(t_D^4) + 1.7016E-03(t_D^3) - 5.9210E-02(t_D^2) + 8.6932E-01(t_D) + 9.1772E-01
	$t_D > 40$	W_{eD} = 5.625
4	$t_D \leq 50$	W_{eD} = -6.6544E-06(t_D^4) + 8.5806E-04(t_D^3) - 4.0134E-02(t_D^2) + 8.2026E-01(t_D) + 1.0631E+00
	$t_D > 50$	W_{eD} = 7.499

4.5	$t_D \leq 100$	$W_{eD} = -8.7131E-07(t_D^4) + 2.1096E-04(t_D^3) - 1.7911E-02(t_D^2) + 6.2956E-01(t_D) + 1.7400E+00$
	$t_D > 100$	$W_{eD} = 9.625$
5	$t_D \leq 120$	$W_{eD} = -4.8331E-07(t_D^4) + 1.4181E-04(t_D^3) - 1.4698E-02(t_D^2) + 6.4146E-01(t_D) + 1.7227E+00$
	$t_D > 120$	$W_{eD} = 12.000$
6	$t_D \leq 220$	$W_{eD} = -6.6466E-08(t_D^4) + 3.5633E-05(t_D^3) - 6.7348E-03(t_D^2) + 5.3036E-01(t_D) + 2.6570E+00$
	$t_D > 220$	$W_{eD} = 17.500$
7	$t_D \leq 500$	$W_{eD} = -4.5918E-09(t_D^4) + 5.4080E-06(t_D^3) - 2.1981E-03(t_D^2) + 3.5619E-01(t_D) + 5.1933E+00$
	$t_D > 500$	$W_{eD} = 24.000$
8	$t_D \leq 500$	$W_{eD} = -4.7668E-09(t_D^4) + 5.8055E-06(t_D^3) - 2.4877E-03(t_D^2) + 4.4082E-01(t_D) + 4.1325E+00$
	$t_D > 500$	$W_{eD} = 31.500$
9	$t_D \leq 500$	$W_{eD} = -4.7035E-09(t_D^4) + 5.7621E-06(t_D^3) - 2.5508E-03(t_D^2) + 4.9147E-01(t_D) + 3.6649E+00$
	$t_D > 500$	$W_{eD} = 40.036$
10	$t_D \leq 500$	$W_{eD} = -3.1762E-09(t_D^4) + 4.3054E-06(t_D^3) - 2.1740E-03(t_D^2) + 4.9849E-01(t_D) + 3.5078E+00$
	$t_D > 500$	$W_{eD} = 49.420$

Table 7
Comparison of the water influx determination among the Van Everdingen-Hurst method, the proposed equations, and the equations of Edwardson et al. for infinite aquifer cases

t, days	t_D	Dimensionless water influx W_{eD}			Cumulative water influx We, Mbbl			% difference	
		vE-H	Proposed	Edw.	vE-H	Proposed	Edw.	Proposed	Edw.
0	0								
100	10.99	7.94	7.82	8.07	55.74	54.89	56.70	1.53	1.73
117	12.86	8.89	8.82	9.04	123.46	121.98	125.51	1.20	1.66
404	44.42	22.67	22.84	22.80	240.04	240.47	242.28	0.18	0.94
660	72.56	33.36	33.30	33.45	431.87	432.54	433.93	0.15	0.48
							MARE	0.77	1.20

Table 8 shows the validation results of the proposed equations for the finite aquifer example. The table illustrates that the cumulative water input estimations of the proposed equations accord well with the Van Everdingen-Hurst technique. The percentage variation in water influx estimated using the Van Everdingen-Hurst approach equations ranges from 0.03% to 3.02%. Furthermore, the table reveals that the estimates of cumulative water influx of the proposed equations are more accurate than the equations from Edwardson et al. This is because Edwardson et al. derived general equations for larger dimensionless time intervals. The MARE values of the proposed equations and the equations of Edwardson et al. are 1.18% and 3.45%, respectively.

Other information obtained from Table 8 is that the predictions of cumulative water influx using the equations of Edwardson et al. provide an increasingly larger percentage difference compared to the predictions of the Van Everdingen-Hurst method with increasing production time. This is because the Edwardson equations were derived for infinite aquifer conditions where the effect of the outer boundary of the aquifer was ignored.

CONCLUSIONS

Based on the analysis and discussion above, the following statements can be made. The proposed equations have good agreement with the Van

Everdingen method with an average difference of 0.77% and 1.18% for the cases of infinite aquifer and finite aquifer, respectively. Additionally, the proposed equations provide more accurate predictions of cumulative water influx compared to the equations of Edwardson et al. for both infinite aquifer cases and finite aquifer cases.

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