Review paper

WATER CONING PREDICTION REVIEWCONTROL: DEVELOPING AN INTEGRATED APPROACH

Abstract

In petroleum industry, oil production strategy to circumvent water coning in reservoirs with strong water drive is quit challenging. To ameliorate this oil production related problem, several water coning prediction models and control approaches have been developed by researchers. The prediction approaches include analytical, empirical and numerical approach. The analytical and empirical prediction approaches are qualitative water coning prediction approach with limited field scale application. However, these approaches model predictions can again field application if upscale. Numerical approach has provided the fulcrum to study the complexity of water coning phenomenon in bottom-water drive reservoirs, and its prediction and sensitivity results have found wide field application. In addition, the various developed water coning control methods: downhole oil-water separation (DOWS), downhole water sink (DWS), downhole water loop (DWL), among others have proved to be effective, as it reduces the water-cut, produced water and water handling problem at the surface during hydrocarbon production. However, the challenge of producingthe bypassed oil in the reservoir remains unattended with these coning control methods. Also, even as effective as these water coning control methods may seems, they have their drawbacks that limit their application in certain reservoirs. Therefore, developing integrated approach that is adaptive to control water coning and produce bypassed oil in bottom-water drive reservoirs is important to the oil and gas industry.

Keywords:Water coning;Water drive reservoir;Coning prediction approach;Coning control methods;Total penetration;Water shut-off; Horizontal well; Downhole water sink; Downhole water loop; Integrated approach

1. Introduction

In oil and gas production, proper planning and development strategies are put in place to avert any production-related-problems. One of such problems is coning and/or cusping; depending on the coned fluid (i.e., water or gas) into the well. Coning is a fundamental petroleum engineering problem since oil is very often found below a gas zone, or above water zone or sandwiched between these two zones (Ike and Debasmita, 2013). The production of water from oil producing wells is a common occurrence in oil field, which results from one or more reasons such as normal rise of oil water contact, water coning and water fingering (Saad*et al.,* 1995). In general, coning or cresting are the term used to describe the mechanism underlying the upward movement of water and/or the downward movement of gas into the perforations of a producing well (Okwananke and Isehunwa, 2008). This phenomenon is as a result of fluids segregation according to their densities, when gravitational forces are exceeded by the flowing pressure - viscous force. In most oil and gas field over the world, produced water due to coning is normally present in the reservoir even before production start; as in bottom water aquifer and/or in artificially improved recovery scheme, and as in water injection (Ibelegbu and Onyekonwu, 2010). Therefore, the production of excessive water and/or gas has been a continuing problem for operators since the beginning of petroleum industry (Jin, 2009). Additionally, Inikori (2002) mentioned that produced water problem exist in North Sea and in the Niger Delta, as well as in the Middle East. Thus, water in general is produced from oil wells at a water cut that depends on the well and reservoir characteristics (Shadizadeh and Ghorbani, 2001). Water coning is characterized by the gradual growth of cone of water in the vertical and radial directions. Namani*et al.* (2007) maintained that in conventional reservoirs the extent of cone growth and/or its stability depend on factors such as: mobility ratio, oil zone thickness, the extent of the well penetration and vertical permeability; with total production rate being the most important. In addition, Saleh and Khalaf (2009) were of the opinion that water coning depended on the properties of the porous media, oil-water viscosity ratio, distance from the oil-water interface to the well, production rate, densities of the fluids and capillary effects. Unlike conventional reservoirs, coning phenomenon in fractured reservoirs is more challenging and complicated due to the intrinsic difference in them along with the heterogeneity and high permeable medium of the fractures compared to matrixes (Foroozesh*et al*., 2008). Therefore, the study of water coning behaviour requires good understanding of reservoir geology, water production (water cut) history profile, reservoir pressure changes, gas-oil ratio (GOR), and material balance analysis (Bae, 2015). Hence, maximizing oil recovery in a reservoir with underlain water and overlain gas is a challenge because coning or cresting of unwanted fluids is inevitable (Kabir*et al.,* 2004). Thence, delaying the encroachment and production of gas and water are essentially the controlling factors in maximizing the field's ultimate oil recovery (Ahmed, 2006). Since production of oil and/or gas involves the flow of formation fluid into the wellbore, several coning prediction and control approaches have been developed to mitigate the formation of water and/or gas coning in the near wellbore. Therefore, this paper evaluates the various water coning prediction approaches and the control methods to propose an integrated approach to avert water coning during production of oil and gas from the reservoir.

2. Mechanism of Water Coning

In bottom-water drive reservoirs, water coning is a production-related-problem in partially perforated wells, that is, wells completed at the upper parts of the reservoir. During production of oil, the pressure drop in the well tends to draw-up water from the aquifer towards the lowest completion interval at the well; as shown in Figure 1. This rising up of aquifer content - water, is caused by potential distribution near the wellbore. Worth noting that since the moment the well is produced, water cone is formed as a result of potential difference between the oil and water phase. In this connection, Gan (2015) reported that the upward movement of water cone depends on vertical potential gradient, activity of aquifer, vertical permeability, fractional well penetration, drainage radius, well radius, and water-oil density contrast. Additionally, since water is more mobile that oil owing to viscosity difference, when the same potential gradient is applied; water velocity seems higher than that of oil. Consequently, the oil-water-contact below oil completion interval rises towards the perforation. In infinite acting reservoirs with inactive or weak aquifer, if the production is sufficiently low, the viscous force is offset by gravity contrast between the oil and water phase. Hence the water cone becomes stable and cease rising toward the completion interval. However, when the production rate increases, the cone height above the oil water contact (OWC) also increases. At a certain moment where gravity contrast of water and oil cannot offset their mobility differences, water cone becomes unstable and rises towards the well perforation intervals. Thence, water coning becomes eminent and breakthrough - water production at the well, is unavoidable.

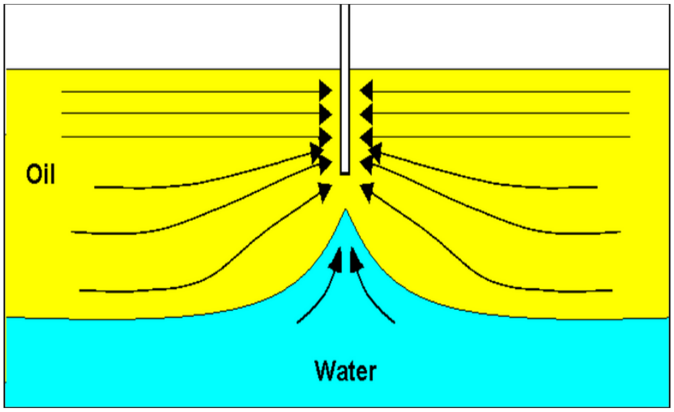

Figure 1: Schematic of Water Coning into a Well (Bekbauov*et al.,* 2012)

3. Water Coning Predictions

In the production of oil from hydrocarbon reservoirs with strong water-drive or aquifer, it is likely that the well(s) in the field will experience water coning when produced for a long period. Also, when producing at high production rate, water coning occurs in a more pronounced manner earlier than expected. This result in accelerated water production that cannot be controlled anymore (Bae, 2015). In the literature, several studies have been performed to predict and mitigate water coning in the production of oil and gas. The early study of water and/or gas coning phenomenon was based on the understanding of well and coning configurations; as depicted in Figure 2. Several authors have developed correlations to predict coning problem in terms of critical oil rate; that is, the maximum production oil rate without producing water, water breakthrough time, and water-oil ratio (WOR) after breakthrough. Among these, critical oil rate is probably the most discussed coning parameter (Osisanya*et al.,* 2000). Generally, these correlations formulation can be divided into two categories. The first category determines the correlations analytically based on the equilibrium conditions of viscous and gravity forces in the reservoir. While the second category is based on empirical correlations developed from laboratory experiments or computer simulation. Nowadays, there had been a shift from the former approach of developing the empirical correlations to the later; due to the complexity of reservoirs engineering problems and the recent advances in computer technology (Recham, 2001). Additionally, the computer based approach of coning study has provided a more reliable avenue of assessing reservoir parameters and well completion has they affect coning phenomenon during oil and gas production. Nevertheless, irrespective of the coning study approach, critical rate, breakthrough time and water cut performance after breakthrough still remain the yardstick for predicting and evaluating coning phenomenon in petroleum reservoir during the production of oil and gas.

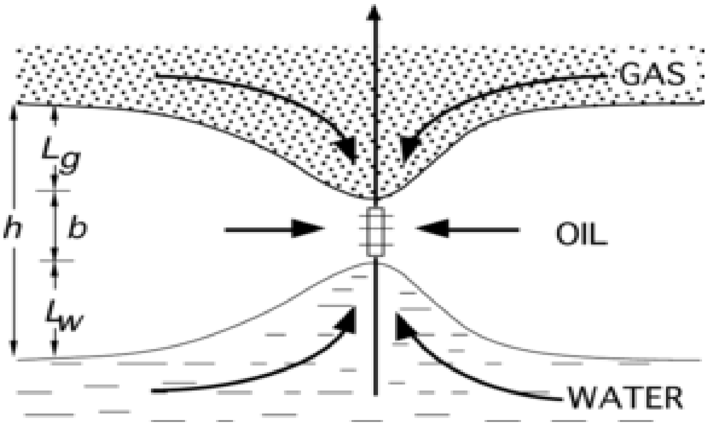

Figure 2: Gas and Water Coning Schematic in Producing Well (http://petrowiki.org)

a. Analytical Approach

The early study of water coning phenomenon analytically was pioneered by Muskat and Wyckoff (1935). They presented an approximate analytical solution for the total pressure drop using graphical method to obtain the critical coning rate. Authur (1944) then extended the Muskat and Wyckoff (1935) theory to include simultaneous water and gas coning. Thereafter, Authors like Meyer and Gardner (1954), Chaney *et al.* (1956) and Hoyland*et al.* (1989) expanded Muskat and Wyckoff (1935) work to include different assumptions to establish coning critical rate. In 1964, Chierice*et al.*presented the effect of reservoir geometry and well configuration on critical coning rate and optimum perforation interval for simultaneous gas and water coning. Also, Chappelear and Hirasaki (1976) derived a coning model based on vertical equilibrium and segregated flow for a radially symmetric, homogeneous, anisotropic permeability system. Wheatley (1985) accounted for the influence of cone shape on the oil potential which other authors had not done before. Chaperon (1986) presented the critical flow rate for the onset of water coning for vertical and horizontal wells. He added that the critical coning rate increases with decrease in vertical permeability. Further studies by Piper and Gonzalez (1987) extended the Wheatley's (1985) work to handled three-phase calculation for critical rate and optimum completion interval. They maintained that neglecting the effect of cone rise on fluid potential causes the estimated critical rate to be 20 to 25 percent higher than the actual field critical rate. Furthermore, Abbas and Bass (1988) studied the performance of water coning under different boundary conditions analytically, experimentally and numerically. For analytical approach, they derived solution for calculating the water-free oil rate for steady state and pseudo-steady state flow conditions in a two-dimensional radial flow system using an average pressure concept. Although the two-dimensional radial flow assumption and average pressure concept are not suitable for water coning systems Recham*et al.* (2000), they were the first researchers to establish the effect of limited wellbore penetration on the critical cone rate. Guo and Lee (1992) and Guo*et al.* (1992) have presented a graphical analysis of water coning on the oil productivity of a well. The analytical solution is for an optimum wellbore penetration into oil zone to maximize the critical oil rate for an isotropic oil zone. Also, Guo*et al.* (1992) work presented an analytical solution which is used to determine water-oil interface location in an anisotropic reservoir. Again, Tabatabaei*et al.* (2012) presented analytical solution for water coning in vertical wells. They developed a model that predicts critical rate and optimum wellbore penetration to achieve maximum water-free production rate in vertical oil wells. The developed model was based on radial, spherical and combined three-dimensional flow that looks into the effect of permeability anisotropy, fluid density difference, and wellbore penetration.

In all, most of the analytical coning studies in the literature focused on establishing critical flow rate in vertical wells with few works on horizontal wells. Some of this analytical approach correlations are presented in Table 1-A in the Appendix A. Conversely, Alikhan and Ali (1985) earlier mentioned that water coning problem is highly complex, therefore, an analytical solution is not possible. However, to develop an effective control strategy against coning, certain theoretical aspects regarding coning must be understood. Therefore, to develop analytical solutions, certain assumptions must be made. These assumptions limit the practical applicability of these analytical solutions. Hence, the most reliable way to study coning is with a specially designed finite-difference simulator (Letkeman and Ridings, 1970; Fetkovitch*et al.,* 1998). That notwithstanding, certain analytical solutions and empirical correlations can be helpful and serve as a preliminary guide for water coning predictions.

b. Empirical Approach

Numerous laboratory studies of water coning have been reported in the literature. The early work used an analog model: Hele-Shaw or potentiometric for the study. Meyer and Searcy (1956) used the Hele-Shaw model to predict water breakthrough time and the steady state water-oil ratio (WOR). Also, Henley *et al.* (1956) presented the first scaled-model laboratory experiments to study oil recovery by bottom water drive. They examined the effects of rate of production, fluid mobilities, capillary and gravity forces, well penetration and well completion techniques on the oil recovery performance using unconsolidated sand pack model with permeability range from 30 to 250 darcies. Additionally, Smith and Pirson (1963) investigated the method to control water coning by injecting oil at a point below the producing interval. They reported that water-oil ratio (WOR) was reduced by the injected fluid, and the reduced water-oil was improved if the injected fluid was more viscous than the reservoir oil or a zone of reduced permeability exists in the vicinity of the injection point. In addition, they maintained that for a given oil production rate, the optimum point of fluid injection was the point closest to the bottom of the producing interval that does not interfere with the oil production. Before then, Karp *et al.* (1962) earlier considered several factors involved in creating, designing and locating (i.e., above the production perforation) horizontal barrier for controlling water coning. They performed experiments to test the suitability of various materials as impermeable barriers. Then, they concluded that reservoirs with high-density or high-viscosity crude oil, very low permeabilities or small oil-zone thickness may be poor candidate for the barrier treatment. On the other hand, Sobocinki and Cornelius (1965) developed a correlation that predicts the onset of water coning based on laboratory data and modelling results. In their correlation, they expanded the breakthrough time and cone height in dimensionless forms involving those scaling factors: water-oil density difference, oil-zone thickness, oil viscosity, oil formation volume factor, porosity and oil flow rate, considered important to coning. Khan (1970) looked at water influx in three-dimension scaled laboratory model. The model used a porous sand pack and modelled fluids to represent thin oil and water layers. The result of the study indicated that mobility ratio has a significant influence on the value of the water-cut and degree of water coning at a given total production rate. Also, for mobility ratios less than unity, the water cones have relatively lower profiles and greater radial spread. Additionally, for higher mobility ratios, the water cone experiences an initial rapid rise followed by a radial spread. Furthermore, Bournazel and Jeanson (1971) developed a method for coning onset prediction combining experimental correlations with a simplified analytical approach. They used dimensionless number to estimate breakthrough time based on the assumptions that the front shape behaves like a current line, in an equivalent model of different shape. Equally, this approach can be used to determine the optimum completion and withdrawal.

On the other hand, Schols (1972) presented empirical critical rate correlations for partially penetrated wells in isotropic and anisotropic reservoirs. These correlations were based on laboratory experiments using Hele-Shaw model and mathematical simulations. Then, Mungan (1979) conducted a laboratory study of water coning in a layered model test bed where fluid saturation was tracked as a function of time and location. The experiments accounted for the effect of viscosity and production rate on the behaviour of the water cone, the effect of heterogeneity in the test bed, and the effect of injection of polymer slug at the oil-water contact before water injection were conducted. He maintained that high oil viscosity or high production rate result in low recovery and high water-oil ratio (WOR) for the same water injection. Also, the injected polymer solution at the water-oil contact would delays development of water cone. However, in all the various laboratory experiments to study water coning parameters, no attempt was made to look at saturation and pressure distribution in the test bed as a function of time. Rajan and Luhning (1993) mentioned that the lack of this information inhibited a better understanding of the coning phenomenon. Then, they experimentally considered the use of cold, non-condensable gas injection into an oil reservoir with bottom water as an effective method for water coning suppression. Their studies revealed that the injected gas migrates towards the production well along the oil-water interface as a blanket thereby increasing the free gas saturation. Also, the injected gas creates a three phase region of oil, water and gas which resulted in reduced relative permeability for water flow and the residual oil saturation. Jiang and Butler (1998) conducted experimental investigation of the effect of flow rates and viscosity ratios on the stability of coning interface and on oil recovery at breakthrough. They established that oil recovery at breakthrough decreased with flow rate and viscosity ratio. Conversely, where viscosity ratio was high, the oil recovery at high flow rate formed multiple fingers with high oil recovery than low flow rates with considerable amount of oil. Shevchenko (2013) performed experiments to study water coning phenomenon in perforated pipes geometry. Analysis of his results showed that water coning in the annulus geometry directly depends on the fluid flow rate, high oil viscosity and annulus width. Nevertheless, Menouar and Hakim (1995) noted that most experimental studies performed on scaled petrophysical models may not provide all the answers to reservoir engineering problems due to the difficulty of scaling some of the reservoir parameters. Thus, the empirical approach of water coning studies is also faced with the mentioned challenge. Some empirical approach correlations to predict critical rate (q_c), breakthrough time (t_{bt}) and cone height (h_c) are presented in Table 2-A (Appendix A).

c. Numerical Approach

A lot of computer simulations to handled coning problem in the petroleum reservoir have been made available in the literature. Researchers have conducted sensitivity studies to delineate the relative importance of various parameters in coning phenomena. The first numerical approach of coning study was performed by Welge and Weber in 1964. They applied two-phase, two-dimensional model using the alternating direction implicit procedure (ADIP) in the gas and water coning simulation. Then, they stated that a special computational technique must be used after cone breakthrough to achieve reliable results and keep calculation costs within reasonable limits. In addition, they suggested that the average horizontal to vertical permeability (K_h/K_v) ratio is critical parameter in the coning study. Also, Pirson and Metha (1967) developed a computer program to simulate water coning based on the Welge and Weber's mathematical model. They studied the effects of various factors: vertical to horizontal permeability ratio, oil-water mobility ratio, specific gravity differential between the two phases and flow rate on the advance of a water cone. The obtained results were found to agree with known phenomenon. However, comparison of their results with Muskat's approximate method, they reported that Muskat's method gives high critical rate as it ignores the water-oil transition zone.MacDonald and Coats (1970) described and evaluated three methods for the simulation of well coning behaviour. They improved upon the small time step restriction of coning problems by making the production and transmissibility terms implicit, and this increase the simulation speed much more than the traditional IMPES (Implicit Pressure Explicit Saturation) method. They concluded that fully implicit model accepts larger time increment sizes and is more efficient for problems involving high capillary forces but requires more computer time. They further recommended radial model with fine grid around the wellbore for vertical well conceptual studies. Furthermore, Letkeman and Ridings (1970) proposed a numerical coning model that exhibits stable saturation and production behaviour during cone formation and after breakthrough. The stability of their model finite difference equation was due to production rate and mobilities implicit extrapolation at the new time level.In 1972, Kaneko and Mungan performed a numerical simulation study on oil reservoir with bottom water. Their results showed that water breakthrough time and water-oil ratio (WOR) increased significantly as the production rate increase. Then, Bryne and Morse (1973) presented a systematic numerical coning simulation study which included the effects of reservoir and well parameters. They reported that increase in well penetration depth reduced the water-free oil production rate (critical rate). They further added that there was no significant effect of wellbore radius on water-oil ratio and breakthrough time. Also, Miller and Rogers (1973) presented detailed coning simulation which was suitable to evaluate water coning problem for a single well in a reservoir with bottom water. They simulated a single well using radial coordinates and a grid system which could be used to determine the most important parameters in water coning on both short-term and long-term production. Interestingly, their simulated results for critical oil rate matched well with Schols' (1972) critical rate correlation prediction. Aziz *et al.* (1973) simulated two-phase coning model to predict the coning phenomenon for two wells in the Sylvan Lake, Pekisko B Pool. The obtained results were compared with available history to investigated reservoir parameters such as horizontal permeability, vertical permeability near the wellbore, and pressure maintenance by water or oil influx. Their obtained model result was used to explain some interesting aspects of the coning problem for the two wells.

On the other hand, Mungan (1975) performed both experimental and numerical model studies of water coning into oil producing well under two-phase, immiscible and incompressible flow conditions. The obtained results indicated higher oil recovery and lower water-oil ratio (WOR) when the production rate, well penetration, vertical permeability and well spacing were decreased; or when the horizontal permeability and the ratio of gravity to viscous forces were increased. Also, Blades and Stright (1975) simulated water coning behaviour of undersaturated, high viscous oil reservoirs; pressure maintained by bottom water drive. The multi-rate performance of two wells was matched with two-dimensional coning model to investigate the sensitivities of some reservoir fluid and rock properties. The study considered necessary to include capillary pressure in the model to history match the coning behaviour and develop a set of type curves (defined by oil zone thickness and oil viscosity) to predict coning behaviour and ultimate recovery in the specified reservoir. In addition, Abougoush (1979) developed correlation from the results of a sensitivity study for heavy oil pool (reservoir) where water coning was a frequent problem. He reported that a coning correlation which combines the important parameters into dimensionless groups can be derived for the heavy oil cases in a way that a single curve is adequate to define the water-oil behaviour. Additionally, he pointed out that oil production decline rapidly and stabilized at a fraction of the initial productivity, but the stabilized value was not sensitive to the oil zone thickness. Kuo and Desbrisay (1983) used a numerical approach to determine the sensitivity of water coning behaviour to various reservoir parameters. From the simulation results, they developed a simplified correlation to predict the water-cut in bottom water drive reservoirs. Also, they provided a simplified model programmed on a hand held calculator which can conveniently predict critical rate, water breakthrough time and water cut performance without lengthy computations on expensive computer. Yang and Wattenbarger (1991) developed water coning correlation similar to Addington's gas coning correlation to predict critical rate, breakthrough time and water-oil ratio after breakthrough. They used radial model with logarithmic grid distribution for vertical wells and a 3-Dimensional Cartesian model for horizontal well studies with finer grid distribution around the wellbore and coarser grid away from the wellbore. Menouar and Hakim (1995) studied the effects of various reservoir parameters such as anisotropy ratio and mobility ratio on water coning behaviour. For horizontal wells, most of the studies presented the critical rate as an increasing function of anisotropy ratio (α). Their study shows that this assertion is valid only for $0.5 < \alpha < 1$, and for $0.01 < \alpha < 0.1$, the critical rate is strongly decreasing function of anisotropy ratio. Inikori (2002) reported that several other authors including Wu *et al*. (1995) and McMullan and Larson (2000) used a 3-Dimensional Cartesian model with finer grid in the oil zone and coarser grid in the water zone together with implicit type commercial numerical simulator for water coning studies in horizontal wells. Worth noting that, most of the numerical coning studies from 1990s were focused on horizontal wells or both vertical and horizontal wells. Makinde*et al*. (2011) simulated water coning behaviour in horizontal wells and pointed out that the oil column height below perforation is the critical criterion for coning behaviour in horizontal well. He also added that reservoir porosity contributes to delay of water coning into the horizontal well. Then, Rustum (2015) compared between empirical water coning models and single-well simulated model with actual field performance. He maintained that some of the empirical models can be considered more reliable than the others, however, the single-well numerical model gives a more reliable history matched water-cut performance than the empirical correlations. In all, irrespective of the numerical solution formulation and reservoir model, the basic numerical simulation flow chart is presented in Figure 1-A (Appendix A).Nevertheless, numerical approach of water coning study in reservoirs has provided the locus for understanding the complexity of the phenomenon in bottom-water drive reservoirs, as the obtained results and models have been used in wide field application.

3.1. Water Coning Control Methods

Several approaches have been invented to develop water-drive reservoirs efficiently and economically. Researchers began to seek ways to control water coning problem - a predominant challenge of developing water-dive reservoir, shortly after knowing the coning phenomenon. Numerous practical solutions have been developed to delay the water breakthrough time and minimize the severity of water coning in vertical wells (Jin, 2005). These practical approaches include: separating oil and water in the oil-water contact (OWC) using horizontal impermeable barriers (Karp *et al.,* 1962), controlling the fluids mobility in the reservoir (Smith and Pirson, 1963), producing oil below its critical rate (Abbas and Bass, 1988), completing the upper section of the pay zone (Guo and Lee, 1993), using horizontal wells (Joshi, 1991) and producing oil and water separately by downhole water sink (DWS) as well as downhole water loop (DWL) (Wojtanowicz*et al*., 1991; Siemek and Stopa, 2002; Jin, 2005, among others). However, some of these proposed water coning control methods have drawbacks or limited field applications. For instance, even the completing of the upper section of the pay zone also requires producing below the critical rate; which is not economical. When using water shut-off with chemicals, the well may be damaged when the polymer or gel barrier enters the oil completion (Jin*et al.,* 2009). On the other hand, Chugbo*et al.* (1989) reported that horizontal wells are not always a solution to water coning problem, as they are constrained by drilling technology. Therefore, downhole water sink (DWS) and downhole water loop (DWL) technology are attractive water coning attenuation methods, which are proven to be effective methods to reduce water coning in vertical oil completions. Thus, their field applications cannot be overemphasized.

i. Perforation Squeeze-off and Re-completion

In some reservoir where shale barriers are inter-bedded with the sandstone as in laminated sands, the shale barriers could form effective seal between the sand layers. The sandstone - high permeable sand, layers in contact with the water zone are often times responsible for the high water influx in to the production interval. This zone could be isolated by squeeze cement during workover operation to minimize the level of water production. Most times, the entire perforation is completely squeezed off and the well re-completed away from the new oil-water contact. Goodwin (1984) mentioned that water production through coning can be altered by squeeze cementing only if the water is flowing through natural or created fractures, or through annular channels in the primary cement sheath. Also, Inikori (2002) added that this operation would not be feasible if adequate zonal isolation is not possible due to absence of shale barrier streaks.

ii. Conformance Technology - Water Shut-off

According to Halliburton (2017) conformance technology is the application of processes to a wellbore or reservoir to help reduce production of unwanted water and/or gas to efficiently enhance hydrocarbon recovery and/or satisfy a broad range of reservoir management and environmental objectives. On the other hand, water shut-off involves an operation that hinder water to reach and/or enter the production well(s) during oil and gas production. This technique is used worldwide to avoid the massive water production. To achieve this objective, chemical conformance technology: sealant and relative permeability modifier are used. Sealants are preferred materials that selectively seal a water producing zone that can be mechanically or chemically isolated. Relative permeability modifiers are polymer treatments that can be designed to reduced water flow from the treated area with very minimum damage to the production of oil and gas. However, several literatures have gave case histories of field applications of these technologies, their long term effect on reservoir properties and overall well performance remains a controversy to industry operators (Inikori, 2002). Thus, some of the fields with water shut-off technology are presented in Table 1.

Table 1: Some Fields with Water Shut-off Technology to Control Water Coning

Source	**Field Name**	**Location**	**Reservoir Formation**
Al-Khawajah and MacDonald (1995)	Aramco Field	Saudi Arabia	Limestone
Wibowo*et al.* (1999)	Offshore North West Java (ONWJ) Field	Indonesia	
Al-Mutairi*et al*. (2003	South Umm Gudair Field	Between Kuwait and Saudi Arabia	
Uddin *et al.* (2003)	WafraRatawi Field	Kuwait	
Al-Umran*et al.* (2005)	Ghawar Field	Saudi Arabia	
Mata *et al*. (2006)	Boscan Field	Venezuela	Sandstone
Al-Dhafeeri*et al*. (2012)	Al-Khafji Field		

iii. Total Penetration Method

This method simply involves the extension of perforation interval to traverse the entire pay (oil) zone and into the bottom water zone to maintain radial flow of fluids (i.e., oil and water) into the wellbore. The approach is to avoid development of cone and attendant oil bypass. Consequently, the production of water starts immediately as oil production commences. Therefore, water handling facilities are put in place to accommodate the excess produced water at the surface. However, over time as the production continues the tendency for cone development is unavoidable (Ehlig-Economides *et* *al.,*1996). Also, Inikori (2002) mentioned that the combined production of high volume of water and oil in one production string create unwanted environmental problem cause by the disposal of the contaminated water.

iv. Horizontal Well Technology

Horizontal wells are high-angle wells with an inclination of generally greater than 85° drilled to enhance reservoir performance by placing a long wellbore section within the reservoir (www.petrowiki.org). Figure 3 shows the schematic of horizontal well configuration in the oil zone of a reservoir. Joshi (2003) mentioned that the purpose of horizontal wells are to enhance well productivity, reduced water and gas coning, intersect natural fractures and to improve well economics. Conversely, this well technology that seems as coning suppression method also experience coning phenomena if the production rate is too high. However, the production rate that may result in coning in horizontal well is far higher than its vertical counterpart. As earlier alluded to, Chugbo*et al.* (1989) maintained that horizontal wells are not always a solution to water coning problem, as they are constrained by drilling technology. Additionally, this well technology can only drained one pay zone per horizontal well and its high cost of 1.4 to 3 times more than a vertical well (www.petroblogweb.wordpress.com) is a concern.Some of the early successful application of horizontal wells in water coning control as reported by Lacy *et al.* (1992), Gilman *et al.* (1995) and Hamada *et al.* (2001) are presented in Table 2.

Table 2: Some Successful Field Application of Horizontal Wells in Water Coning Control

Source	**Field Name**	**Location**	**Reservoir Type**
Lacy *et al.* (1992)	Prudhoe Bay Field Alaska Field Helder Field Troll Field	North Sea, Norway	Sandstone
	North Herald Field South Pepper Field Chervil Field	Australia	
	Rospo Mare Field Bima Field	Italy Indoesia	Limestone
Gilman *et al.* (1995)	Yates Field	West Texas, USA	Thin Oil Column
Hamada *et al.* (2001)	Marjan Field Zuluf Field Safaniya Field Abqaiq Field	Arabian Gulf, Saudi Arabia	Carbonate
El-Gogary*et al.* (2015)	Belayim Field	Gulf of Suez	

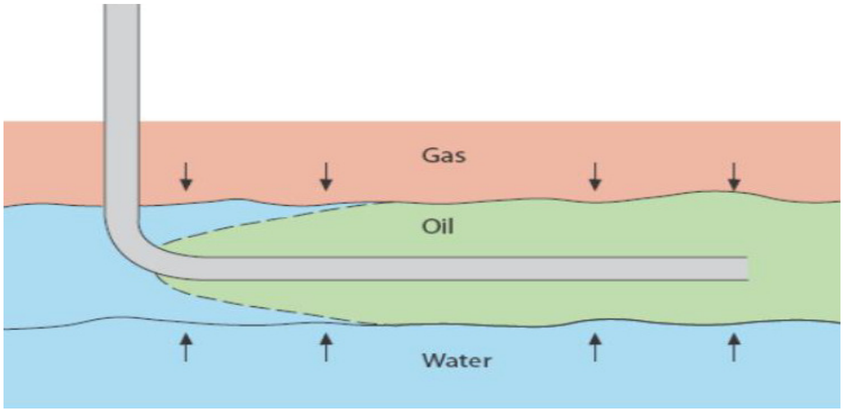

Figure 3: Horizontal Well Schematic (Shaibu*et al.*, 2017)

v. *Downhole Oil-Water Separation Technology*

Downhole oil-water separation (DOWS) involves the use of hydrocyclone separators and special design downhole pumps installed in the completion/production string to separate the oil and water mixture within the wellbore. Figure 4 depicts a typical configuration of the downhole oil-water separation technology. This technology has been in the oil and gas industry since the 1990s, however, despite its economic and environmental advantages, only a limited number of the system has been installed in the oil and gas wells (Abdullah and Ahmed, 2015). This development is due to the complexity of the technology, as wellbore space is very limited. Thus, the hydrocyclone designed (must be narrow) for the operation hindered the minimum casing size requirement. Additionally, Inikori (2002) opined that the technology provides reduced surface water handling, but the fundamental problem of water interference with oil production within the reservoir creating bypass oil still remains unresolved with this technology. Therefore, the problem of bypassed oil by the water cone development is not mitigated by this technology.However, Abdullah and Ahmed (2015) presented some fields withDOWS technology installation (Table 3).

Table 3: Some Fields with DOWS Technology Installation for Water Coning Control

Field Name	**Location**	**Operator's Name**	**Well Name**
Redwater Field	Alberta	Imperial Redwater	#1-26
Alliance Field		Pinnacle-Alliance	06D
Alliance Field		Pinnacle-Alliance	07C
Alliance Field		Pinnacle-Alliance	7C2
Provost Field		PanCanadian	00/11C-05
Provost Field		PanCanadian	00/11A2-05
Provost Field		PanCanadian	00/16-05
East Texas	Texas	Texaco Dickson	#17
Rangely Field	Colorado	Chevron Fee	153X
Salem Field	Illinois	Texaco Salem	#85-40

Source: Abdullah and Ahmed (2015)

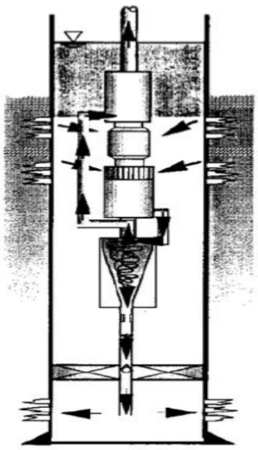

Figure 4: Downhole Oil-Water SeparationSchematic (Abdullah and Ahmed, 2015)

vi. Downhole Water Sink (DWS) Method

Downhole water sink (DWS) is a completion/production technique for producing water-freehydrocarbons from reservoirs with bottom-water-drive and strong tendency towater-coning (Wojtanowicz*et al.,* 1991). It provides an innovate solution for water coning control which canreduce water cut significantly (Gan, 2015), as well as delay the breakthrough time. This technology eliminates water cutting the hydrocarbon production by using hydrodynamicmechanism of coning control in-situ at the oil-water contact(Luiprasert*et al.,* 2013).Basically, DWS involves a dual-completion well withone completed at oil zone for oil production and the other completed at water zone forwater drainage near oil-water-contact. The typical downhole water sink (DWS) system is depicted in Figure 5. In the Figure, the drainage completion provides the extra pressure drop below oil-water-contact whichcan balance the rising force at the oil interval. Thus, this oppose pressure drawdown in the water interval may result in considerably water coning suppression and leads to better water cut control after water breakthrough.

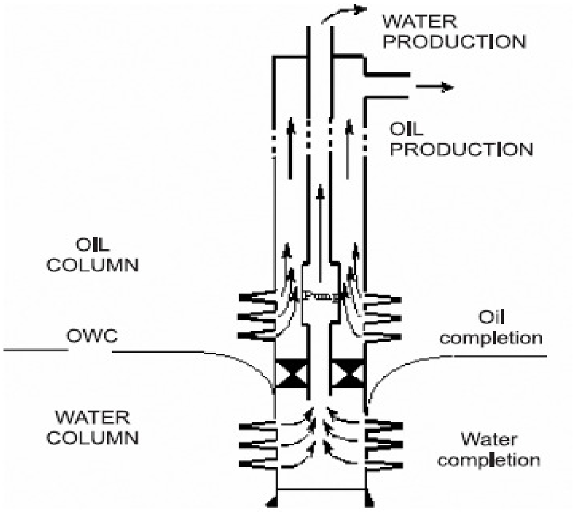

Figure 5: Downhole Water SinkSchematic(Wojtanowicz, 2006)

Downhole water sink (DWS) technology: operational and design, has been studied theoretically (Wojtanowicz*et al.,* 1991; Swisher and Wojtanowicz, 1995) and experimentally (Shirman and

Wojtanowicz, 1997) since 1991. Additionally, numerical simulation study (Inikori, 2002) has justified the feasibility of DWS. After the successful first field implementation of DWS in 1994 by Hunt Petroleum (Swisher and Wojtanowicz, 1995), numerous other companies have tested the technology in the fields and reported good results.These fields trial of DWS technology are presented in Table 4. However, for DWS technology, a look at the total volume of water produced at the surface could be scarily when compared to conventional well. This is because much oil-free water is lifted to the surface; which doesn't require treatment. Therefore, water disposal cost would not increase has a consequence of the technology. Although DWS technology shows great potentials, it requires a large amount of water to be pumped to and handle at the surface, which implies large lifting costs in the production of oil and gas.

Table 4: Some Field trials of DWS Technology in Water Coning Control

Source	**Field Name**	**Location**	**Reservoir Type**
Swisher and Wojtanowicz (1995)	Nepo-Hemphill Field	LaSalle Parish, Louisiana	
Bowlin*et al.* (1997)	Kern River Field	California	
Shirman and Wojtanowicz (1998)		Indonesia	
	Bakers Field	California	
	East Texas Field	Texas	Sandstone
		Canada	

vii. Downhole Water Loop (DWL)

Downhole water loop (DWL) technology was developed on the basis of downhole water sink (DWS) well/completion to cushion the set back (i.e., handling of huge volume of water at the surface), experienced with the DWS technology. It involves a triple-completed well: one perforation located at oil zone and the other two located at water zone. These three completions are separated by two packers unlike the DWS completion with single packer. The top most completion at the oil zone is used for oil production while the second completion - water drainage interval (WDI), is used to produce water simultaneously near the oil-water contact to stabilize the interface. The produced water at the WDI is re-injected into the same aquifer through the lowest completion - water re-injection interval (WRI) using submersible pump. A typical configuration of downhole water loop (DWL) is shown in Figure 6. However, Jin*et al.* (2009) reported that the efficiency of DWL strongly depends upon the vertical distance between the two water looping completions: water drainage and water re-injection intervals. Thus, the dependence of the DWL technology on water looping completions interval limits its application in reservoir with small size water zone (aquifer).Regrettably, no field application of the downhole water loop technology has been reported in the literature.

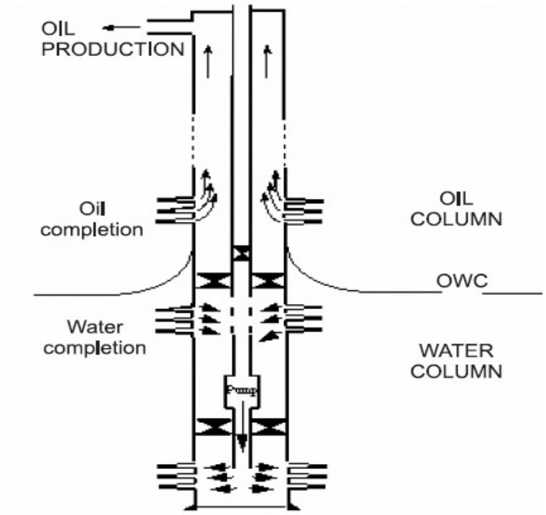

Figure 6: Downhole Water LoopSchematic (Wojtanowicz, 2006)

viii. Intelligent Completions

Completions that enable reservoir engineers to monitor and control production or injection in at least one reservoir zone are known as intelligent or smart completion. Such technology is proving to be a reliable and cost-effective way for better reservoir management. Intelligent or smart wells are basically wells fitted with special downhole completions equipment that measure and monitor well conditions and reservoir parameters such as flow rate, fluid composition, bottomhole temperature and pressure (Shaibu*et al.,* 2017). In addition, Kwame *et al.* (2014) mentioned that intelligent wells have downhole control valves to regulate, seal portions of the wellbore and optimize the movement of hydrocarbon into the well to enhance oil recovery. Therefore, intelligent well technology can provide an effective way to deal with water coning by deploying special downhole instrumentation which can be operated remotely (Guevara-Addiegro*et al*., 2008). Thus, it protects operations from the risks associated with early water or gasbreakthroughs and from crossflow between producing zone in the same well. A typical smart well completion configuration is depicted in Figure 7.

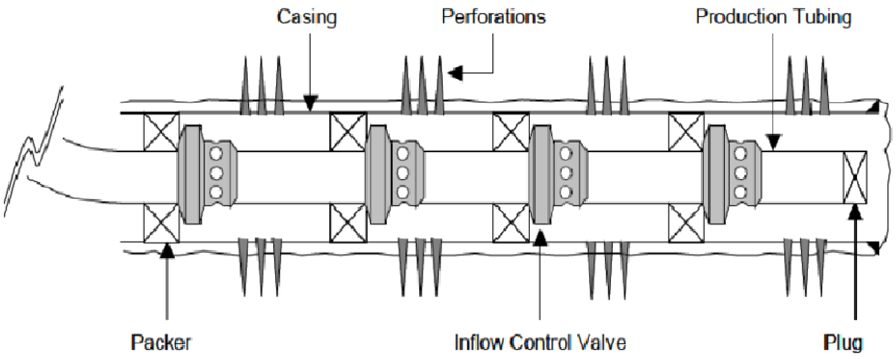

Figure 7: Intelligent Well CompletionSchematic (Aderemi, 2012)

Intelligent completions just like other water coning attenuation methods have its drawbacks. Intelligent wells are very expensive due to the high cost of installed inflow control devices, control cables and lines, isolation feed-through packers, and the surface control data gathering systems.

Cullick and Sukkestad (2010) added that the reliability of the downhole valves and sensors are factors for consideration in intelligent well(s) completion. Also, identification of potential and suitable candidates for intelligent well technology is a major concern (Arashi, 2007).

4. Learnings from the Review

The various water coning control approaches mostly addresses two major challenges of water coning phenomenon; which are, increased water cut and water handling problems at the surface during oil production. However, the challenge of bypassed oil in the reservoir as a result of water coning around the wellbore remains unattended to with the numerous water coning attenuation methods. Thus, Table 5 presents the various water coning control methods as well as the suitable candidate reservoir(s) for the applied control method. In summary, this paper has assessed the existing water coning prediction correlations approaches and control methods. The analytical and empirical prediction approaches are qualitative water coning prediction approach that lacks field scale application. However, some of the existing correlations based on analytical and empirical approached require upscaling to gain field scale application. Nevertheless, these approaches have provided insight on this phenomenal production problem - water coning, in bottom-water drive reservoirs. In addition, numerical study of the water coning problem in reservoirs has provided both qualitative and quantitative approaches to the problem. Thus, the approach has showcased some reservoir's parameters that influence the phenomenon in bottom-water drive reservoirs. Therefore, with high quality field data input, correlations from this approach can be widely applied to fields. On the other hand, water coning control methods: downhole water sink (DWS) and downhole water loop (DWL) as well as the proposed thin horizontal downhole water loop (THDWL) are the most efficient control measures for the phenomenal production problem. However, the screening criteria for the candidate reservoir for their full implementation become of essence. The challenges of surface water handling in DWS and aquifer size limitation for DWL are worrisome, despite their field success. Additionally, the recent intelligent/smart well completion that sense water and/or gas encroachment in to the wellbore is promising. Its sensing potential may sometime be misleading in cases of channelling, casing leakages, among others. Also its automatic shut-in is another considerable factor in its use for water coning control. Therefore, an integrated approach that considers the outlined drawbacks in the water coning control methods is important. Hence, there is need for integrated water coning controls in bottom-water drive reservoirs. The approach that is adaptive to implement the appropriate water coning control measures as well as handle the challenge of bypassed oil in the reservoir.Thus, the proposed integrated approach should incorporate two or more control approaches at a time.

Table 5: Comparison of Some Water Coning Control Methods

	Control Methods	**Completion**	**Advantage(s)**	**Limitation(s)**	**Candidate Reservoir**
i.	Production below critical production rate; q_c		Low water cut; no water production at the surface. Longer time to reach breakthrough.	The production rate is not economical.	Both water-drive reservoirs with active and inactive (weak) aquifer.
ii.	Perforation far from oil-water contact (OWC)	The perforation interval is placed at a predetermined distance far from the oil-water contact	Delayed the breakthrough time. The oil production rate can be slightly above the critical rate	It is limited by the oil column thickness (pay zone) of the reservoir	Conventional and thin-oil rim reservoirs with both active and inactive aquifer.
iii.	Total penetration	The perforation interval covers the entire oil column (zone) and extended distance below oil-water contact (OWC) into the water layer	Oil production rate would be greater than critical production rate. Delayed breakthrough time; low water cur	The height of the oil column or zone is the determining factor	Thin-oil rim reservoirs; especially with inactive aquifer
iv.	Vertical well gel treatments	Injecting polymers or gels to form a barrier between oil and water zones	Delayed breakthrough time and reduce water cut	The polymers or gels may plug the reservoir pore connectivity which can impaired fluid flow The well may damage when the polymer or gel barrier enters the oil completion	Both water-drive reservoirs with inactive and active aquifer
v.	Horizontal wells	Drill horizontal well into the oil zone	Compared to vertical well in the same oil zone, it provide delayed breakthrough time and high oil recovery potentials	Horizontal wells are constrained by drilling technology. It is expensive than its conventional counterpart.	Conventional and thin-oil column reservoirs with both weak and active aquifer
vi.	Downhole oil-water separation technology	Well completed with installed hydrocyclone and pumps to separate water from oil mixture	Production of water free oil at the surface, reduce water handling at the surface, etc.	Hindered the minimum casing size requirement	Conventional and thin-oil column reservoirs with both weak and active aquifer are candidate
vii.	Downhole water sink (DWS)	Dual completion; above and below the oil-water contact (OWC)	Increase critical rate and low water cut. Delayed or breakthrough time	Production of water and handling problems. More energy consumption and high lifting cost Completion of dual zone is expensive than conventional (single) well	Conventional reservoir with large active aquifer
viii.	Downhole water loop (DWL)	Triple completion; one above oil-water contact and two below OWC (i.e., one completion at DI and other at DWI)	Increase critical rate and low water cut, with delayed breakthrough time; Better performance at reservoir pressure maintenance; No production and handling of water at the surface, Less energy and consumption cost of water pump	Due to complexity and water coning dynamic, it requires careful design of the production system; Limited by the thickness of the aquifer; Completion of three intervals is expensive	Weak (inactive) bottom-water drive reservoirs
ix.	Thin-horizontal downhole water loop (THDWL)	Quadruple (four) completion; one above OWC for production of oil and three below OWC.	Handling the drawback observed in the DWS and DWL. Less or low water cut than DWS and DWL	Very expensive than DWS and DWL completion approach	Both water drive reservoir with weak and active aquifer.

	Control Methods	Completion	Advantage(s)	Limitation(s)	Candidate Reservoir
x.	Intelligent or smart completions	Well completed with installed inflow control valves (ICVs), sensors, gauges, etc.	Monitor, regulate and measure reservoir and fluid parameters Increase reservoir productivity	Very expensive due to high cost of installed ICVs, etc. Reliability of the downhole valves and sensor are considerable factors for monitoring and control	Conventional and thin oil column reservoirs with high recoverable reserves are possible candidate

5. An Integrated Approach

The proposed integrated approach considered in this study to control water coning phenomenon in bottom-water drive reservoirs is based on the works of Smith and Pirson (1963), Hoyt (1974) and Paul and Strom (1988) combine with the downhole water loop (DWL) technology. Smith and Pirson (1963) and Hoyt (1974) suggested injection of part of the produced fluid into the formation below the production completions to build pressure gradient barriers to suppress water coning. Also, Paul and Strom (1988) proposed injection of water-soluble polymeric gel to control bottom-water mobility. In this connection, the proposed integrated approach involves the use of producer and injector wells. The producer well has a typical completion of DWL technology, that is, one completion at the oil zone and two completions (i.e., water drainage interval and water re-injection interval) at the water zone. The injector well has two completions, one completed near the water oil contact (WOC) and the other completion interval located few depths below the WOC. The configuration of the proposed integrated approach wells completion is depicted in Figure 8. The upper completion in the injector well injects water-soluble polymeric gel in to the pay zone to sweep the bypassed oil in the reservoir to the wellbore of the producer well. Then lower completion injects the polymeric gel in to the water zone (aquifer) to reduce the mobility of the bottom water. With the inclusion of the DWL completions, at the water zone, the supposed encroach water is drain through the WDI and re-injected into the aquifer. These moves ensure that the pressure gradient at the wellbore is maintained. Thus, the coning of water in to the wellbore is suppress, hence,produced water volume at the surface is minimal Therefore, it is expected that this integrated approach will handle the challenge of producing bypassed oil in the reservoir, suppress water coning in bottom-water drive reservoirs and provide additional recovery potential to the reservoir.

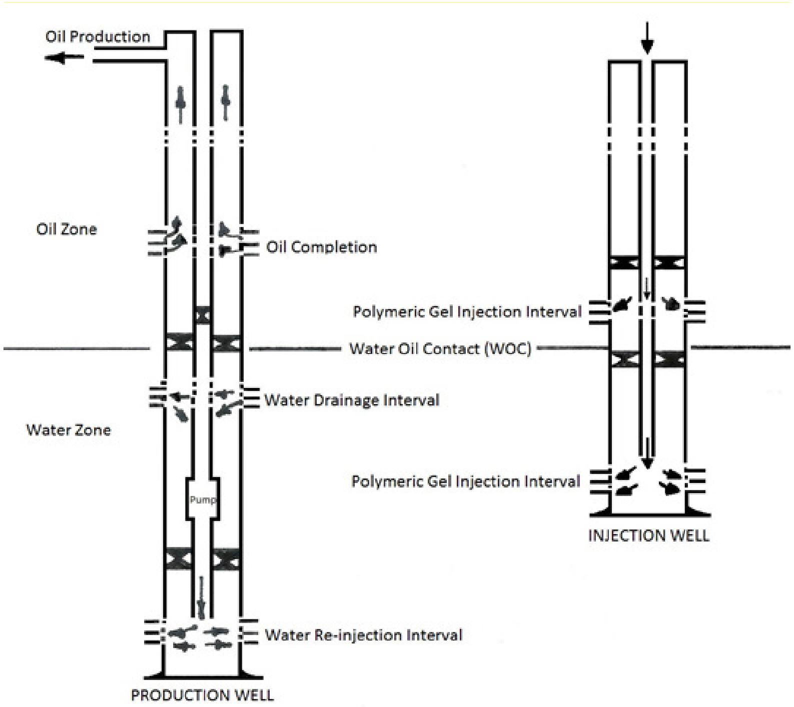

Figure 8: Well Completions of the Proposed Integrated Approach

Conclusion

Controlling encroached water into the wellbore from aquifer in most bottom-water drive reservoirs during oil and gas production is very challenging throughout the productive life of the well. Thus, several coning prediction correlations and control approaches have been propound by researchers. However, some of these developed correlations alongside the control methods have found wide application but their predictions vary from reservoir to reservoir. Therefore, the need to develop integrated approach that extends the application of the numerous water coning control methods is of essence. In the course of this, the various water coning prediction approaches and control methods are reviewed and the following conclusions are drawn:

i. analytical and empirical water coning prediction correlations require upscaling to gain field scale application;
ii. numerical simulation approach provides an effective method to study the complexity of water coning phenomenon in reservoir, especially where quality data from the field are available;
iii. most developed water coning control methods have handled increase water-cut and water production as well as water handling problems at the surface during hydrocarbon production, but the challenge of producing the bypassed oil in the reservoir remain a concern; and
iv. the proposed integrated approach should provide a more robust method to mitigate water coning problem in bottom-water drive reservoirs.

Nomenclature

$\mu_o =$ critical rate, *stb/d*
$\Delta\gamma =$ water-oil density difference, *psi/ft*
$\mu_o =$ oil viscosity, *cp*
$\mu_w =$ water viscosity, *cp*
$r_w =$ wellbore radius, *ft*
$r_e =$ drainage radius, *ft*
$h =$ pay-zone thickness, *ft*
$h_p =$ height of completion interval, *ft*
$k_v =$ vertical permeability, *md*
$k_h =$ horizontal permeability, *md*
$t_{bt} =$ breakthrough time, *hr*
$h_c =$ cone height, *ft*
$B_o =$ oil formation volume factor, *rb/stb*
$M =$ mobility ratio
$g =$ gravity constant, *ft/hr*^{2}
$\varphi =$ porosity, *fraction*
$\alpha =$ mobility ratio exponent
$\psi_w =$ dimensionless water function
$\varepsilon =$ fraction of oil column height above perforation

δ_w = fraction of perforation interval

r_D = dimensionless radius

t_D = dimensionless time

Z_D = dimensionless cone height

$(t_D)_{bt}$ = dimensionless breakthrough time

q_{CD} = dimensionless critical rate

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APPENDIX A

Table 1-A: Some Analytical Approach Correlations for Critical Rate Prediction

	Author(s)	**Analytical Correlations**
1.	Meyer and Gardner (1954)	$q_c = \left[\dfrac{2.63\times10^{-6} k_o \Delta\gamma \left(h^2 - h_p^2\right)}{\mu_o B_o \ln\left(\dfrac{r_e}{r_w}\right)}\right]$
2.	Chaney *et al.* (1956)	$q_c = \left[\dfrac{3.33\times10^{-6} k_o \Delta\gamma}{\mu_o B_o}\right]\left[0.225\left(h^2 - h_p^2\right) - 3.69\right]$
3.	Chierici*et al.* (1964)	$q_c = \left[\dfrac{4.92\times10^{-5} h^2 \Delta\gamma}{\mu_o B_o}\right]\left(k_{ro}k_h\right)\psi_w\left(r_D, \varepsilon, \delta_w\right);\ r_D = \dfrac{r_e}{h}\sqrt{\dfrac{k_v}{k_h}}\ \varepsilon = \dfrac{h_p}{h}\ \delta = \dfrac{D_b}{h}$
4.	Chaperon (1986)	$q_c = 8.63\times10^{-7}\left[\dfrac{k_h \Delta\gamma \left(h - h_p\right)^2}{\mu_o B_o}\right]\left(0.7311 + \dfrac{1.943}{r_D}\right)$
5.	Abbas and Bass (1988)	Stead State Flow Condition: $q_c = \dfrac{5.25\times10^{-6} k_h h_p \Delta\gamma \left(h - h_p - h_{ap}\right)}{\mu_o B_o \left(\dfrac{r_e^2}{r_e^2 - r_w^2}\ln\dfrac{r_e}{r_w} - \dfrac{r_e^2 + r_w^2}{4r_e^2} - \dfrac{1}{2}\right)}$ Unsteady State Flow Condition: $q_c = \dfrac{5.25\times10^{-6} k_h h_p \Delta\gamma \left(h - h_p - h_{ap}\right)}{\mu_o B_o \left(\dfrac{r_e^2}{r_e^2 - r_w^2}\ln\dfrac{r_e}{r_w} - \dfrac{r_e^2 + r_w^2}{4r_e^2} - \dfrac{1}{2}\right)}$
6.	Hoyland*et al.* (1989)	$q_c = 2.63\times10^{-6}\left(\dfrac{h_o^2 \Delta\gamma k_h}{\mu_o B_o}\right) q_{CD}$
7.	Guo and Lee (1992)	$q_c = 1.68\times10^{-5}\dfrac{k_v \Delta\gamma}{\mu_o}\left[r_e - \sqrt{r_e^2 - r_e\left(h - h_p\right)}\right]^2\left[\dfrac{k_v}{\sqrt{k_h^2 + k_v^2}} + \dfrac{h_p\left(\dfrac{1}{r_w} - \dfrac{1}{r_e}\right)}{\ln\dfrac{r_e}{r_w}}\right]$

	Author(s)	Analytical Correlations
8.	Tabatabaei*et al.* (2012)	$q_c = \frac{7.08\times10^{-3} k_h \Delta\gamma \left(h - h_p - r_w\right)}{\mu_o \left(\frac{1}{r_w} - \frac{1}{r_e}\right)} \left[\frac{1}{\sqrt{\left(\frac{k_v}{k_h}+1\right)}} + \frac{h_p\left(\frac{1}{r_w}-\frac{1}{r_e}\right)}{\ln\frac{r_e}{r_w}} \right]$

Table 2-A: Some Empirical Approach Correlations

	Author(s)	Empirical Correlations
		Critical Rate
1.	Bournazel and Jeanson (1971)	Isotropy Reservoir: $q_c = 5.14\times10^{-5} \frac{k_h h^2 \Delta\gamma g}{\mu_o}\left(1-\frac{h_p}{h}\right)$ Anisotropy Reservoir: $q_c = 5.14\times10^{-5} \frac{k_h^2 h^2 \Delta\gamma g}{\mu_o k_v}\left(1-\frac{h_p}{h}\right)$
2.	Schols (1972)	$q_c = 7.83\times10^{-6}\left[\frac{\Delta\gamma k_o\left(h^2-h_p^2\right)}{\mu_o B_o}\right]\left[0.432+\frac{\pi}{\ln\frac{r_e}{r_w}}\right]\left(\frac{h}{r_e}\right)^{0.14}$
		Breakthrough Time and Cone Height
1.	Sobocinki and Cornelius (1965)	$t_{bt} = 7.30\times10^{2}\frac{\mu_o \varphi h F_k}{\Delta\gamma k_h\left(1+M^{\alpha}\right)}\left(t_D\right)_{bt}$ Where; $\left(t_D\right)_{bt} = \frac{Z_D}{4}\left(\frac{16+7Z_D-3Z_D^2}{7-2Z_D}\right)$ $\alpha = 0.5$ for M < 1; 0.6 for 1 < M ≤ 10 $h_c = 3.26\times10^{2}\frac{\mu_o q_o B_o}{\Delta\gamma k_h h} z_D$
2.	Bournazel and Jeanson (1971)	$t_{bt} = 7.30\times10^{2}\frac{\mu_o \varphi h F_k}{\Delta\gamma k_h\left(1+M^{\alpha}\right)}\left(t_D\right)_{bt}$ Where; $\left(t_D\right)_{bt} = \frac{Z_D}{3-0.7Z_D}$ $\alpha = 0.7$ when 0.14 < M ≤ 7.3

$$F_k = k_h / k_v$$

$$M = \frac{\mu_o k_{rw@Sor}}{\mu_w k_{ro@Swc}}$$

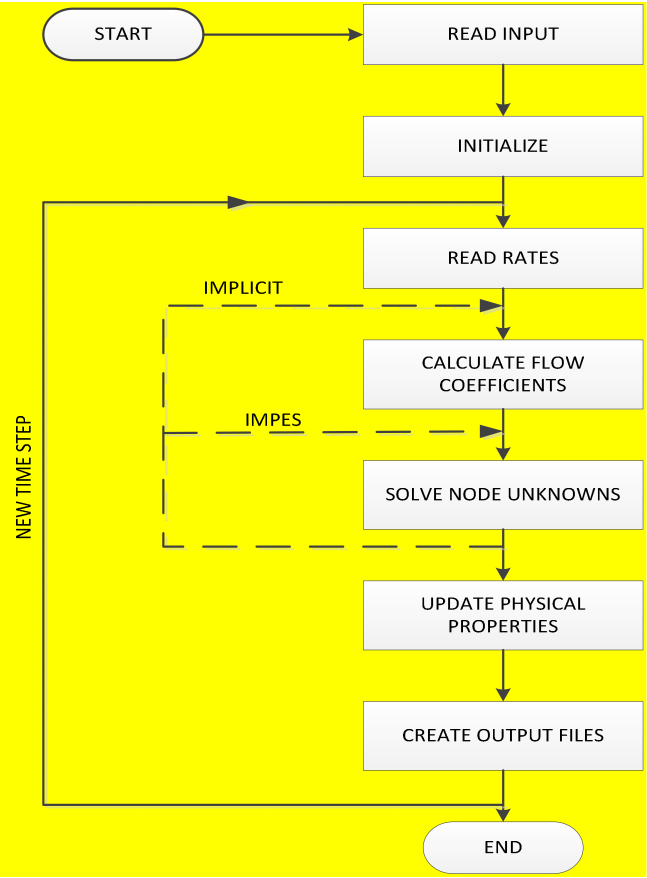

Figure 1-A: Typical Numerical Simulation Flow Chart (Fanchi, 2001)