

WATER CONING PREDICTION REVIEW AND CONTROL: 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 producing the bypassed oil in the reservoir remains unattended with these coning control methods. Also, even as effective as these water coning control methods may seem, 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 (Saadet *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 (Shadzadeh and Ghorbani, 2001). Water coning is characterized by the

47 gradual growth of cone of water in the vertical and radial directions. Namani *et al.* (2007) maintained
48 that in conventional reservoirs the extent of cone growth and/or its stability depend on factors such as:
49 mobility ratio, oil zone thickness, the extent of the well penetration and vertical permeability; with
50 total production rate being the most important. In addition, Saleh and Khalaf (2009) were of the
51 opinion that water coning depended on the properties of the porous media, oil-water viscosity ratio,
52 distance from the oil-water interface to the well, production rate, densities of the fluids and capillary
53 effects. Unlike conventional reservoirs, coning phenomenon in fractured reservoirs is more
54 challenging and complicated due to the intrinsic difference in them along with the heterogeneity and
55 high permeable medium of the fractures compared to matrixes (Foroozeshet *et al.*, 2008). Therefore, the
56 study of water coning behaviour requires good understanding of reservoir geology, water production
57 (water cut) history profile, reservoir pressure changes, gas-oil ratio (GOR), and material balance
58 analysis (Bae, 2015). Hence, maximizing oil recovery in a reservoir with underlain water and overlain
59 gas is a challenge because coning or cresting of unwanted fluids is inevitable (Kabiret *et al.*, 2004).
60 Thence, delaying the encroachment and production of gas and water are essentially the controlling
61 factors in maximizing the field's ultimate oil recovery (Ahmed, 2006). Since production of oil and/or
62 gas involves the flow of formation fluid into the wellbore, several coning prediction and control
63 approaches have been developed to mitigate the formation of water and/or gas coning in the near
64 wellbore. Therefore, this paper evaluates the various water coning prediction approaches and the
65 control methods to propose an integrated approach to avert water coning during production of oil and
66 gas from the reservoir.

67

68 **2. Mechanism of Water Coning**

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

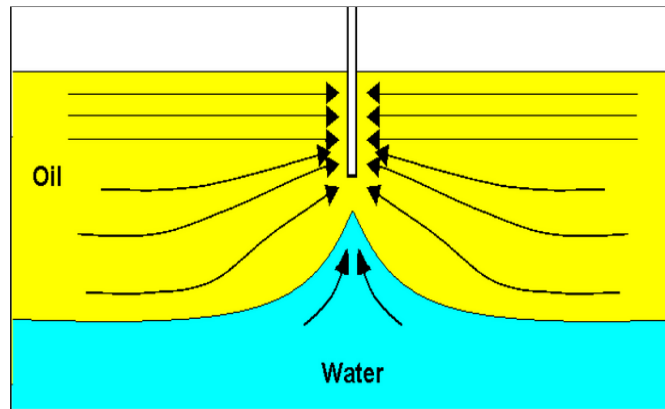
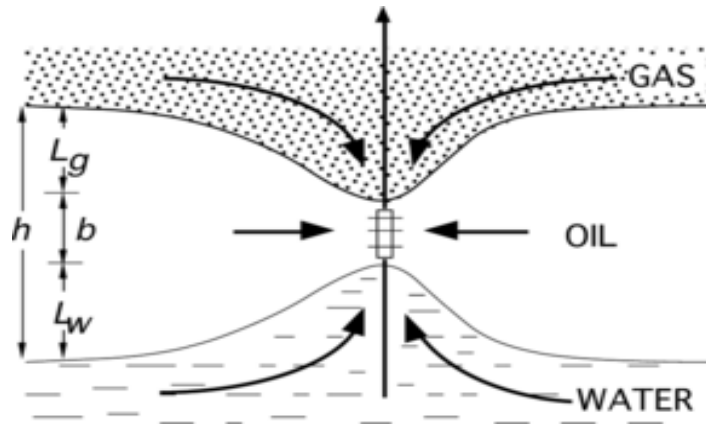


Figure 1: Schematic of Water Coning into a Well (Bekbauovet *al.*, 2012)

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3. Water Coning Predictions

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



113

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

115

a. Analytical Approach

116 The early study of water coning phenomenon analytically was pioneered by Muskat and Wyckoff
 117 (1935). They presented an approximate analytical solution for the total pressure drop using graphical
 118 method to obtain the critical coning rate. Authur (1944) then extended the Muskat and Wyckoff
 119 (1935) theory to include simultaneous water and gas coning. Thereafter, authors like Meyer and
 120 Gardner (1954), Chaney *et al.* (1956) and Hoyland *et al.* (1989) expanded Muskat and Wyckoff (1935)
 121 work to include different assumptions to establish coning critical rate. In 1964, Chierice *et al.* presented
 122 the effect of reservoir geometry and well configuration on critical coning rate and optimum
 123 perforation interval for simultaneous gas and water coning. Also, Chapplear and Hirasaki (1976)
 124 derived a coning model based on vertical equilibrium and segregated flow for a radially symmetric,
 125 homogeneous, anisotropic permeability system. Wheatley (1985) accounted for the influence of cone
 126 shape on the oil potential which other authors had not done before. Chaperon (1986) presented the
 127 critical flow rate for the onset of water coning for vertical and horizontal wells. He added that the
 128 critical coning rate increases with decrease in vertical permeability. Further studies by Piper and
 129 Gonzalez (1987) extended the Wheatley's (1985) work to handled three-phase calculation for critical
 130 rate and optimum completion interval. They maintained that neglecting the effect of cone rise on fluid
 131 potential causes the estimated critical rate to be 20 to 25 percent higher than the actual field critical
 132 rate. Furthermore, Abbas and Bass (1988) studied the performance of water coning under different
 133 boundary conditions analytically, experimentally and numerically. For analytical approach, they
 134 derived solution for calculating the water-free oil rate for steady state and pseudo-steady state flow
 135 conditions in a two-dimensional radial flow system using an average pressure concept. Although the
 136 two-dimensional radial flow assumption and average pressure concept are not suitable for water
 137 coning systems Rechamet *al.* (2000), they were the first researchers to establish the effect of limited
 138 wellbore penetration on the critical cone rate. Guo and Lee (1992) and Guo *et al.* (1992) have
 139 presented a graphical analysis of water coning on the oil productivity of a well. The analytical
 140 solution is for an optimum wellbore penetration into oil zone to maximize the critical oil rate for an
 141 isotropic oil zone. Also, Guo *et al.* (1992) work presented an analytical solution which is used to
 142 determine water-oil interface location in an anisotropic reservoir. Again, Tabatabaei *et al.* (2012)
 143 presented analytical solution for water coning in vertical wells. They developed a model that predicts
 144 critical rate and optimum wellbore penetration to achieve maximum water-free production rate in
 145 vertical oil wells. The developed model was based on radial, spherical and combined three-
 146 dimensional flow that looks into the effect of permeability anisotropy, fluid density difference, and
 147 wellbore penetration.

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

158

159 ***b. Empirical Approach***

160 Numerous laboratory studies of water coning have been reported in the literature. The early work used
161 an analog model: Hele-Shaw or potentiometric for the study. Meyer and Searcy (1956) used the Hele-
162 Shaw model to predict water breakthrough time and the steady state water-oil ratio (WOR). Also,
163 Henley *et al.* (1956) presented the first scaled-model laboratory experiments to study oil recovery by
164 bottom water drive. They examined the effects of rate of production, fluid mobilities, capillary and
165 gravity forces, well penetration and well completion techniques on the oil recovery performance using
166 unconsolidated sand pack model with permeability range from 30 to 250 darcies. Additionally, Smith
167 and Pirson (1963) investigated the method to control water coning by injecting oil at a point below the
168 producing interval. They reported that water-oil ratio (WOR) was reduced by the injected fluid, and
169 the reduced water-oil was improved if the injected fluid was more viscous than the reservoir oil or a
170 zone of reduced permeability exists in the vicinity of the injection point. In addition, they maintained
171 that for a given oil production rate, the optimum point of fluid injection was the point closest to the
172 bottom of the producing interval that does not interfere with the oil production. Before then, Karp *et al.*
173 (1962) earlier considered several factors involved in creating, designing and locating (i.e., above
174 the production perforation) horizontal barrier for controlling water coning. They performed
175 experiments to test the suitability of various materials as impermeable barriers. Then, they concluded
176 that reservoirs with high-density or high-viscosity crude oil, very low permeabilities or small oil-zone
177 thickness may be poor candidate for the barrier treatment. On the other hand, Sobocinki and Cornelius
178 (1965) developed a correlation that predicts the onset of water coning based on laboratory data and
179 modelling results. In their correlation, they expanded the breakthrough time and cone height in
180 dimensionless forms involving those scaling factors: water-oil density difference, oil-zone thickness,
181 oil viscosity, oil formation volume factor, porosity and oil flow rate, considered important to coning.
182 Khan (1970) looked at water influx in three-dimension scaled laboratory model. The model used a
183 porous sand pack and modelled fluids to represent thin oil and water layers. The result of the study
184 indicated that mobility ratio has a significant influence on the value of the water-cut and degree of
185 water coning at a given total production rate. Also, for mobility ratios less than unity, the water cones
186 have relatively lower profiles and greater radial spread. Additionally, for higher mobility ratios, the
187 water cone experiences an initial rapid rise followed by a radial spread. Furthermore, Bournazel and
188 Jeanson (1971) developed a method for coning onset prediction combining experimental correlations
189 with a simplified analytical approach. They used dimensionless number to estimate breakthrough time
190 based on the assumptions that the front shape behaves like a current line, in an equivalent model of
191 different shape. Equally, this approach can be used to determine the optimum completion and
192 withdrawal.

193 On the other hand, Schols (1972) presented empirical critical rate correlations for partially penetrated
194 wells in isotropic and anisotropic reservoirs. These correlations were based on laboratory experiments

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

224 *c. Numerical Approach*

225 A lot of computer simulations to handled coning problem in the petroleum reservoir have been made
226 available in the literature. Researchers have conducted sensitivity studies to delineate the relative
227 importance of various parameters in coning phenomena. The first numerical approach of coning study
228 was performed by Welge and Weber in 1964. They applied two-phase, two-dimensional model using
229 the alternating direction implicit procedure (ADIP) in the gas and water coning simulation. Then, they
230 stated that a special computational technique must be used after cone breakthrough to achieve reliable
231 results and keep calculation costs within reasonable limits. In addition, they suggested that the
232 average horizontal to vertical permeability (K_h/K_v) ratio is critical parameter in the coning study.
233 Also, Pirson and Metha (1967) developed a computer program to simulate water coning based on the
234 Welge and Weber's mathematical model. They studied the effects of various factors: vertical to
235 horizontal permeability ratio, oil-water mobility ratio, specific gravity differential between the two
236 phases and flow rate on the advance of a water cone. The obtained results were found to agree with
237 known phenomenon. However, comparison of their results with Muskat's approximate method, they
238 reported that Muskat's method gives high critical rate as it ignores the water-oil transition
239 zone. MacDonald and Coats (1970) described and evaluated three methods for the simulation of well
240 coning behaviour. They improved upon the small time step restriction of coning problems by making

241 the production and transmissibility terms implicit, and this increase the simulation speed much more
242 than the traditional IMPES (Implicit Pressure Explicit Saturation) method. They concluded that fully
243 implicit model accepts larger time increment sizes and is more efficient for problems involving high
244 capillary forces but requires more computer time. They further recommended radial model with fine
245 grid around the wellbore for vertical well conceptual studies. Furthermore, Letkeman and Ridings
246 (1970) proposed a numerical coning model that exhibits stable saturation and production behaviour
247 during cone formation and after breakthrough. The stability of their model finite difference equation
248 was due to production rate and mobilities implicit extrapolation at the new time level. In 1972, Kaneko
249 and Mungan performed a numerical simulation study on oil reservoir with bottom water. Their results
250 showed that water breakthrough time and water-oil ratio (WOR) increased significantly as the
251 production rate increase. Then, Bryne and Morse (1973) presented a systematic numerical coning
252 simulation study which included the effects of reservoir and well parameters. They reported that
253 increase in well penetration depth reduced the water-free oil production rate (critical rate). They
254 further added that there was no significant effect of wellbore radius on water-oil ratio and
255 breakthrough time. Also, Miller and Rogers (1973) presented detailed coning simulation which was
256 suitable to evaluate water coning problem for a single well in a reservoir with bottom water. They
257 simulated a single well using radial coordinates and a grid system which could be used to determine
258 the most important parameters in water coning on both short-term and long-term production.
259 Interestingly, their simulated results for critical oil rate matched well with Schols' (1972) critical rate
260 correlation prediction. Aziz *et al.* (1973) simulated two-phase coning model to predict the coning
261 phenomenon for two wells in the Sylvan Lake, Pekisko B Pool. The obtained results were compared
262 with available history to investigated reservoir parameters such as horizontal permeability, vertical
263 permeability near the wellbore, and pressure maintenance by water or oil influx. Their obtained model
264 result was used to explain some interesting aspects of the coning problem for the two wells.
265 On the other hand, Mungan (1975) performed both experimental and numerical model studies of
266 water coning into oil producing well under two-phase, immiscible and incompressible flow
267 conditions. The obtained results indicated higher oil recovery and lower water-oil ratio (WOR) when
268 the production rate, well penetration, vertical permeability and well spacing were decreased; or when
269 the horizontal permeability and the ratio of gravity to viscous forces were increased. Also, Blades and
270 Stright (1975) simulated water coning behaviour of undersaturated, high viscous oil reservoirs;
271 pressure maintained by bottom water drive. The multi-rate performance of two wells was matched
272 with two-dimensional coning model to investigate the sensitivities of some reservoir fluid and rock
273 properties. The study considered necessary to include capillary pressure in the model to history match
274 the coning behaviour and develop a set of type curves (defined by oil zone thickness and oil viscosity)
275 to predict coning behaviour and ultimate recovery in the specified reservoir. In addition, Abougoush
276 (1979) developed correlation from the results of a sensitivity study for heavy oil pool (reservoir)
277 where water coning was a frequent problem. He reported that a coning correlation which combines
278 the important parameters into dimensionless groups can be derived for the heavy oil cases in a way
279 that a single curve is adequate to define the water-oil behaviour. Additionally, he pointed out that oil
280 production decline rapidly and stabilized at a fraction of the initial productivity, but the stabilized
281 value was not sensitive to the oil zone thickness. Kuo and Desbrisay (1983) used a numerical
282 approach to determine the sensitivity of water coning behaviour to various reservoir parameters. From
283 the simulation results, they developed a simplified correlation to predict the water-cut in bottom water
284 drive reservoirs. Also, they provided a simplified model programmed on a hand held calculator which
285 can conveniently predict critical rate, water breakthrough time and water cut performance without
286 lengthy computations on expensive computer. Yang and Wattenbarger (1991) developed water coning
287 correlation similar to Addington's gas coning correlation to predict critical rate, breakthrough time
288 and water-oil ratio after breakthrough. They used radial model with logarithmic grid distribution for

289 vertical wells and a 3-Dimensional Cartesian model for horizontal well studies with finer grid
290 distribution around the wellbore and coarser grid away from the wellbore. Menouar and Hakim (1995)
291 studied the effects of various reservoir parameters such as anisotropy ratio and mobility ratio on water
292 coning behaviour. For horizontal wells, most of the studies presented the critical rate as an increasing
293 function of anisotropy ratio (α). Their study shows that this assertion is valid only for $0.5 < \alpha < 1$, and
294 for $0.01 < \alpha < 0.1$, the critical rate is strongly decreasing function of anisotropy ratio. Inikori (2002)
295 reported that several other authors including Wu *et al.* (1995) and McMullan and Larson (2000) used
296 a 3-Dimensional Cartesian model with finer grid in the oil zone and coarser grid in the water zone
297 together with implicit type commercial numerical simulator for water coning studies in horizontal
298 wells. Worth noting that, most of the numerical coning studies from 1990s were focused on horizontal
299 wells or both vertical and horizontal wells. Makinde *et al.* (2011) simulated water coning behaviour in
300 horizontal wells and pointed out that the oil column height below perforation is the critical criterion
301 for coning behaviour in horizontal well. He also added that reservoir porosity contributes to delay of
302 water coning into the horizontal well. Then, Rustum (2015) compared between empirical water
303 coning models and single-well simulated model with actual field performance. He maintained that
304 some of the empirical models can be considered more reliable than the others, however, the single-
305 well numerical model gives a more reliable history matched water-cut performance than the empirical
306 correlations. In all, irrespective of the numerical solution formulation and reservoir model, the basic
307 numerical simulation flowchart is presented in Figure 1-A (Appendix A). Nevertheless, numerical
308 approach of water coning study in reservoirs has provided the locus for understanding the complexity
309 of the phenomenon in bottom-water drive reservoirs, as the obtained results and models have been
310 used in wide field application.

311 3.1. Water Coning Control Methods

312 Several approaches have been invented to develop water-drive reservoirs efficiently and
313 economically. Researchers began to seek ways to control water coning problem - a predominant
314 challenge of developing water-drive reservoir, shortly after knowing the coning phenomenon.
315 Numerous practical solutions have been developed to delay the water breakthrough time and
316 minimize the severity of water coning in vertical wells (Jin, 2005). These practical approaches
317 include: separating oil and water in the oil-water contact (OWC) using horizontal impermeable
318 barriers (Karp *et al.*, 1962), controlling the fluids mobility in the reservoir (Smith and Pirson, 1963),
319 producing oil below its critical rate (Abbas and Bass, 1988), completing the upper section of the pay
320 zone (Guo and Lee, 1993), using horizontal wells (Joshi, 1991) and producing oil and water
321 separately by downhole water sink (DWS) as well as downhole water loop (DWL) (Wojtanowicz *et al.*,
322 1991; Siemek and Stopa, 2002; Jin, 2005, among others). However, some of these proposed water
323 coning control methods have drawbacks or limited field applications. For instance, even the
324 completing of the upper section of the pay zone also requires producing below the critical rate; which
325 is not economical. When using water shut-off with chemicals, the well may be damaged when the
326 polymer or gel barrier enters the oil completion (Jinet *et al.*, 2009). On the other hand, Chugboet *al.*
327 (1989) reported that horizontal wells are not always a solution to water coning problem, as they are
328 constrained by drilling technology. Therefore, downhole water sink (DWS) and downhole water loop
329 (DWL) technology are attractive water coning attenuation methods, which are proven to be effective
330 methods to reduce water coning in vertical oil completions. Thus, their field applications cannot be
331 overemphasized.

332 i. Perforation Squeeze-off and Re-completion

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

343 **ii. Conformance Technology - Water Shut-off**

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

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

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

358

359 **iii. Total Penetration Method**

360 This method simply involves the extension of perforation interval to traverse the entire pay (oil) zone
 361 and into the bottom water zone to maintain radial flow of fluids (i.e., oil and water) into the wellbore.
 362 The approach is to avoid development of cone and attendant oil bypass. Consequently, the production
 363 of water starts immediately as oil production commences. Therefore, water handling facilities are put
 364 in place to accommodate the excess produced water at the surface. However, over time as the
 365 production continues the tendency for cone development is unavoidable (Ehlig-Economides et

366 *al.*,1996). Also, Inikori (2002) mentioned that the combined production of high volume of water and
 367 oil in one production string create unwanted environmental problem cause by the disposal of the
 368 contaminated water.

369 *iv. Horizontal Well Technology*

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

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

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

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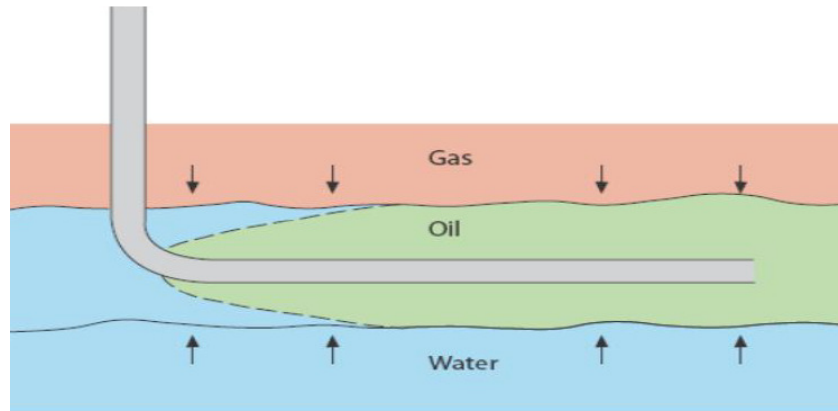


Figure 3: Horizontal Well Schematic (Shaibu et al., 2017)

v. **Downhole Oil-Water Separation Technology**

387

388

389

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

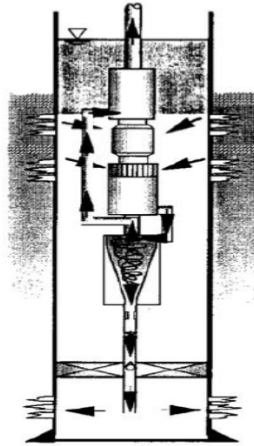
403

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

Field Name	Location	Operator's Name	Well Name
Redwater Field		Imperial Redwater	#1-26
Alliance Field		Pinnacle-Alliance	06D
Alliance Field		Pinnacle-Alliance	07C
Alliance Field	Alberta	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

404

Source: Abdullah and Ahmed (2015)



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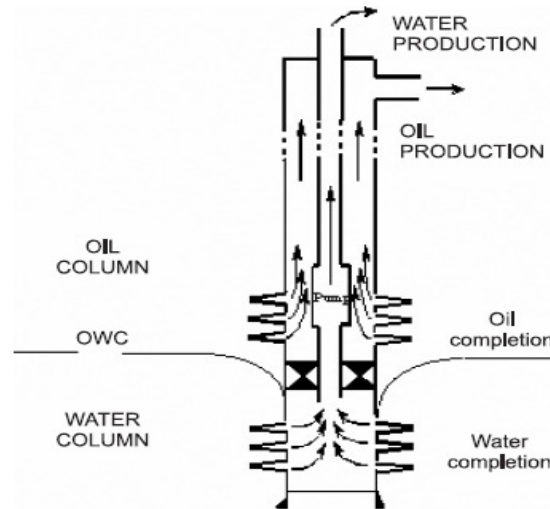
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Figure 4: Downhole Oil-Water Separation Schematic (Abdullah and Ahmed, 2015)

407

vi. Downhole Water Sink (DWS) Method

408 Downhole water sink (DWS) is a completion/production technique for producing water-
 409 free hydrocarbons from reservoirs with bottom-water-drive and strong tendency to water-coning
 410 (Wojtanowicz *et al.*, 1991). It provides an innovative solution for water coning control which can reduce
 411 water cut significantly (Gan, 2015), as well as delay the breakthrough time. This technology
 412 eliminates water cutting the hydrocarbon production by using hydrodynamic mechanism of coning
 413 control in-situ at the oil-water contact (Luiprasert *et al.*, 2013). Basically, DWS involves a dual-
 414 completion well without completed at oil zone for oil production and the other completed at water
 415 zone for water drainage near oil-water-contact. The typical downhole water sink (DWS) system is
 416 depicted in Figure 5. In the Figure, the drainage completion provides the extra pressure drop below
 417 oil-water-contact which can balance the rising force at the oil interval. Thus, this opposite pressure
 418 drawdown in the water interval may result in considerably water coning suppression and leads to
 419 better water cut control after water breakthrough.



420

421

Figure 5: Downhole Water Sink Schematic (Wojtanowicz, 2006)

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

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

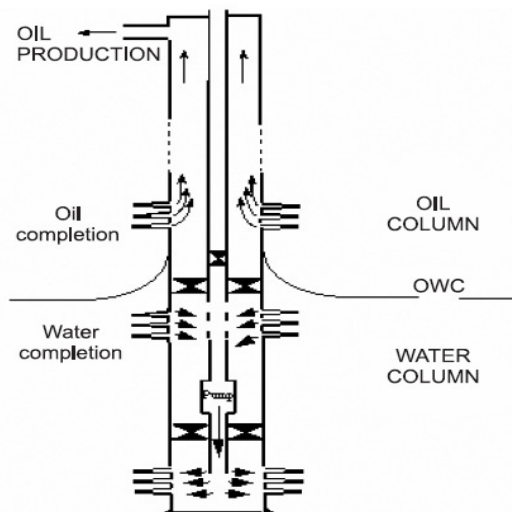
434 **Table 4: Some Field trials of DWS Technology in Water Coning Control**

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

435

436 **vii. Downhole Water Loop (DWL)**

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

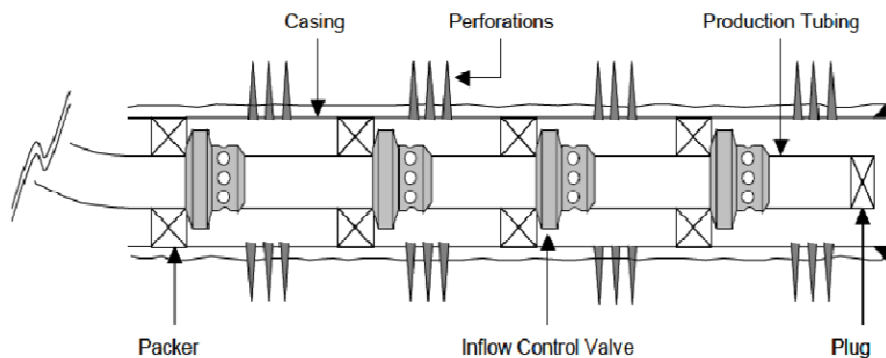


451

452 **Figure 6:** Downhole Water Loop Schematic (Wojtanowicz, 2006)

453 **viii. Intelligent Completions**

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



466

467 **Figure 7:** Intelligent Well Completion Schematic (Aderemi, 2012)

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

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

474 **4. Learnings from the Review**

475 The various water coning control approaches mostly addresses two major challenges of water coning
476 phenomenon; which are, increased water cut and water handling problems at the surface during oil
477 production. However, the challenge of bypassed oil in the reservoir as a result of water coning around
478 the wellbore remains unattended to with the numerous water coning attenuation methods. Thus, Table
479 5 presents the various water coning control methods as well as the suitable candidate reservoir(s) for
480 the applied control method. In summary, this paper has assessed the existing water coning prediction
481 correlations approaches and control methods. The analytical and empirical prediction approaches are
482 qualitative water coning prediction approach that lacks field scale application. However, some of the
483 existing correlations based on analytical and empirical approached require upscaling to gain field
484 scale application. Nevertheless, these approaches have provided insight on this phenomenal
485 production problem - water coning, in bottom-water drive reservoirs. In addition, numerical study of
486 the water coning problem in reservoirs has provided both qualitative and quantitative approaches to
487 the problem. Thus, the approach has showcased some reservoir's parameters that influence the
488 phenomenon in bottom-water drive reservoirs. Therefore, with high quality field data input,
489 correlations from this approach can be widely applied to fields. On the other hand, water coning
490 control methods: downhole water sink (DWS) and downhole water loop (DWL) as well as the
491 proposed thin horizontal downhole water loop (THDWL) are the most efficient control measures for
492 the phenomenal production problem. However, the screening criteria for the candidate reservoir for
493 their full implementation become of essence. The challenges of surface water handling in DWS and
494 aquifer size limitation for DWL are worrisome, despite their field success. Additionally, the recent
495 intelligent/smart well completion that sense water and/or gas encroachment in to the wellbore is
496 promising. Its sensing potential may sometime be misleading in cases of channelling, casing leakages,
497 among others. Also its automatic shut-in is another considerable factor in its use for water coning
498 control. Therefore, an integrated approach that considers the outlined drawbacks in the water coning
499 control methods is important. Hence, there is need for integrated water coning controls in bottom-
500 water drive reservoirs. The approach that is adaptive to implement the appropriate water coning
501 control measures as well as handle the challenge of bypassed oil in the reservoir. Thus, the proposed
502 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

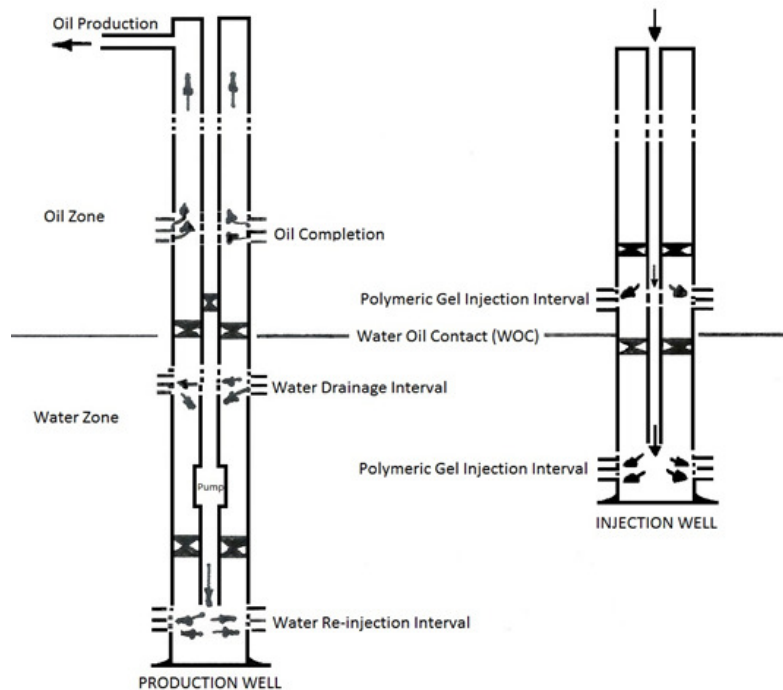
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5. An Integrated Approach

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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.

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Figure 8: Well Completions of the Proposed Integrated Approach

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531 **Conclusion**

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

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

551 **Nomenclature**

- 552 μ_o = critical rate, *stb/d*
- 553 $\Delta\gamma$ = water-oil density difference, *psi/ft*
- 554 μ_o = oil viscosity, *cp*
- 555 μ_w = water viscosity, *cp*
- 556 r_w = wellbore radius, *ft*
- 557 r_e = drainage radius, *ft*
- 558 h = pay-zone thickness, *ft*
- 559 h_p = height of completion interval, *ft*
- 560 k_v = vertical permeability, *md*
- 561 k_h = horizontal permeability, *md*
- 562 t_{bt} = breakthrough time, *hr*
- 563 h_c = cone height, *ft*
- 564 B_o = oil formation volume factor, *rb/stb*
- 565 M = mobility ratio
- 566 g = gravity constant, *ft/hr²*
- 567 ϕ = porosity, *fraction*
- 568 α = mobility ratio exponent
- 569 ψ_w = dimensionless water function
- 570 \mathcal{E} = fraction of oil column height above perforation

571 δ_w = fraction of perforation interval
 572 r_D = dimensionless radius
 573 t_D = dimensionless time
 574 Z_D = dimensionless cone height
 575 $(t_D)_{bt}$ = dimensionless breakthrough time
 576 q_{CD} = dimensionless critical rate
 577

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860 **APPENDIX A**

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

Author(s)	Analytical Correlations
1. Meyer and Gardner (1954)	$q_c = \left[\frac{2.63 \times 10^{-6} k_o \Delta \gamma (h^2 - h_p^2)}{\mu_o B_o \ln \left(\frac{r_e}{r_w} \right)} \right]$
2. Chaney <i>et al.</i> (1956)	$q_c = \left[\frac{3.33 \times 10^{-6} k_o \Delta \gamma}{\mu_o B_o} \right] [0.225 (h^2 - h_p^2) - 3.69]$
3. Chiericiet <i>al.</i> (1964)	$q_c = \left[\frac{4.92 \times 10^{-5} h^2 \Delta \gamma}{\mu_o B_o} \right] (k_{ro} k_h) \psi_w (r_D, \varepsilon, \delta_w); r_D = \frac{r_e}{h} \sqrt{\frac{k_v}{k_h}} \quad \varepsilon = \frac{h_p}{h} \quad \delta = \frac{D_b}{h}$
4. Chaperon (1986)	$q_c = 8.63 \times 10^{-7} \left[\frac{k_h \Delta \gamma (h - h_p)^2}{\mu_o B_o} \right] \left(0.7311 + \frac{1.943}{r_D} \right)$
Stead State Flow Condition:	
5. Abbas and Bass (1988)	$q_c = \frac{5.25 \times 10^{-6} k_h h_p \Delta \gamma (h - h_p - h_{ap})}{\mu_o B_o \left(\frac{r_e^2}{r_e^2 - r_w^2} \ln \frac{r_e}{r_w} - \frac{1}{2} \right)}$
Unsteady State Flow Condition:	
	$q_c = \frac{5.25 \times 10^{-6} k_h h_p \Delta \gamma (h - h_p - h_{ap})}{\mu_o B_o \left(\frac{r_e^2}{r_e^2 - r_w^2} \ln \frac{r_e}{r_w} - \frac{r_e^2 + r_w^2}{4r_e^2} - \frac{1}{2} \right)}$
6. Hoyland <i>et al.</i> (1989)	$q_c = 2.63 \times 10^{-6} \left(\frac{h_o^2 \Delta \gamma k_h}{\mu_o B_o} \right) q_{CD}$
7. Guo and Lee (1992)	$q_c = 1.68 \times 10^{-5} \frac{k_v \Delta \gamma}{\mu_o} \left[r_e - \sqrt{r_e^2 - r_e (h - h_p)} \right]^2 \left[\frac{k_v}{\sqrt{k_h^2 + k_v^2}} + \frac{h_p \left(\frac{1}{r_w} - \frac{1}{r_e} \right)}{\ln \frac{r_e}{r_w}} \right]$

Author(s)	Analytical Correlations
8. Tabatabaeiet al. (2012)	$q_c = \frac{7.08 \times 10^{-3} k_h \Delta \gamma (h - h_p - r_w)}{\mu_o \left(\frac{1}{r_w} - \frac{1}{r_e} \right)} \left[\frac{1}{\sqrt{\left(\frac{k_v}{k_h} + 1 \right)}} + \frac{h_p \left(\frac{1}{r_w} - \frac{1}{r_e} \right)}{\ln \frac{r_e}{r_w}} \right]$

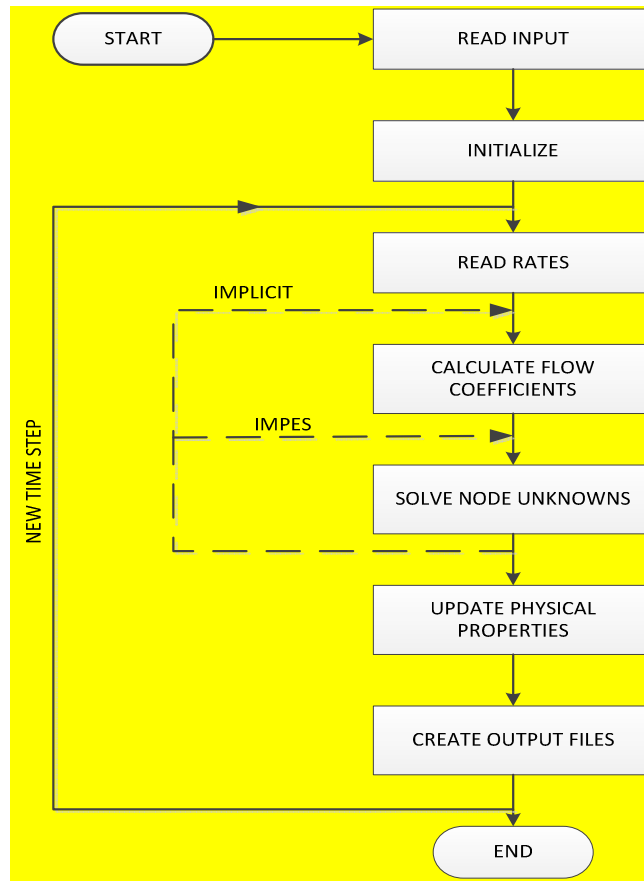
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863 **Table 2-A: Some Empirical Approach Correlations**

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

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