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Preliminary communication

The cost analysis of the separation of produced formation water from the hydrocarbon reservoir using the example of the Upper Miocene sandstone deposits of the Sava Depression

Josip Ivšinović[1]

[1] *INA-Industry of Oil Plc., Trg G. Szabe 1, 44310 Novska, Croatia, e-mail: Josip.Ivsinovic@ina.hr*

Abstract

Formation water is produced during the whole lifetime of a hydrocarbon reservoir alongside the oil and/or gas and it represents the main part of the produced fluid. The produced formation water is separated during the process of dehydration. This paper deals with the formation water separation costs regarding the fields A, B and C which are located in the western part of the Sava Depression. The dehydration process regarding field A is executed in three locations, and in fields B and C, it is executed in one location. The technological system of formation water separation and the geological characteristics of the above-mentioned reservoirs is represented. A statistical analysis regarding the formation water separation costs has been made. The costs have been statistically estimated and a correlation between the costs relevant for the usual formation water separation process has also been made. The purpose of the analysis of the cost of the dehydration process is the optimization of the production system and cost control of the process.

Keywords

Economics formation water, statistical evaluation, cost correlation, Sava Depression

1. Introduction

Formation water is produced during the production from a hydrocarbon reservoir together with oil and/or gas. Globally, oil wells produce about 220 million BWPD (ca. 35 million m^3/day) (**Tajmiri & Reza Ehsani 2016**). The ratio between the produced water and oil is 3:1, and the average share of water in the fluids equals 70% (**Fakhru'l-Razi et al. 2009**). Separation of the formation water is carried out by the dehydration process. The efficiency of formation water separation directly affects the formation water's quality, and its importance for the injection system has been described in the Western Sava depression water-injection system analysis (**Ivšinović 2017**). This paper deals with the costs and the formation water separation process and the geological characteristic of the reservoirs in the oil and gas fields A, B and C. These are located in the western part of the Sava Depression. The dehydration process regarding field A is executed at three locations, and in fields B and C, it is executed at one location. The statistical data was gathered between the years 2009 and 2015. This paper describes the formation water separation process and an estimate will be made regarding the formation water separation costs and the correlation between the important variables in the formation water separation process.

Corresponding author: Josip Ivšinović
Josip.Ivsinovic@ina.hr

2. The Geographic Area of Research and the Basic Geological (Lithostratigraphic) Characteristics of the Area

The oil and gas fields described in this paper are located in the Croatian part of the Pannonian Basin System in the Sava Depression. The geotectonic position of the Sava Depression (blue) within the Pannonian Basin System is shown in **Figure 1**.

The oil and gas field A is located 55 km south-east from Zagreb, and fields B and C are located approximately 90 km south-east from Zagreb. The general and common geographic locations of the fields in question are shown in **Figure 2**, (blue), while the observed reservoirs (blue) are shown in **Figure 3**.

The reservoir rocks of the oil and gas field A are fine to middle grained quartz micaceous sands. On the preneogenic bottom rock, there lies a transgressive complex of neogenic sediments. Within this sediment complex, the main reservoirs are; the sandstones of Lower Pontian, Kloštar Ivanić Formation, Pannonian, and Ivanić-Grad Formation.

The reservoir rocks of oil and gas field B are poorly to fine grained quartz micaceous sandstones. The reservoir structure (see **Figure 4**) is brachyanticline with northwest-southeast general orientation. In field B, the reservoirs are formed in Pliocene and Miocene deposits. The total depth of the reservoirs is between 1 000 and 2 000 meters.

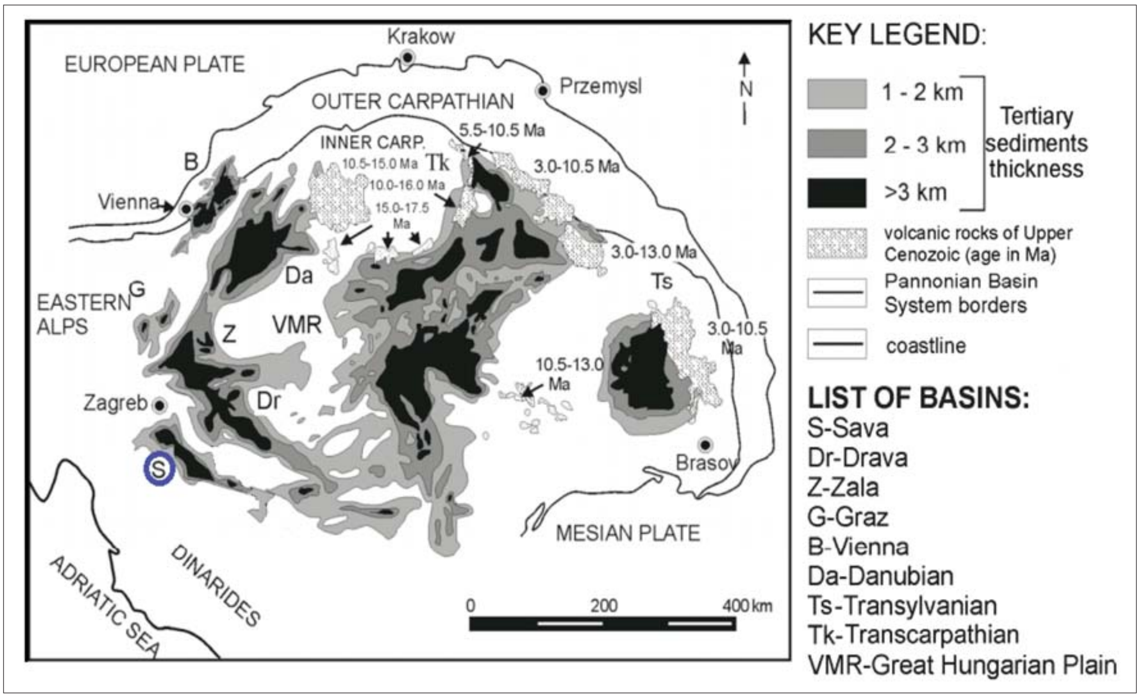

Figure 1: The geotectonic position of the Sava Depression (**modified according to Malvić & Rusan 2009**)

Figure 2: The geographic position of fields A, B and C within the Sava Depression (**Velić et al. 2015**)

The reservoir rocks of oil and gas field C are poorly to middle grained sands and poorly to fine grained quartz micaceous sandstones. The reservoir structure is an elongated anticline with northwest-southeast general orientation. There are two maximums in the central part of the structure. The reservoir rocks are interlayered with marls and sandy marls. Seal rocks are marls that turn into calcitic marls in the deeper reservoirs.

According to **Velić et al. 2012**, oil and gas fields are divided into: large fields (which produced more than 10^6 m^3 of oil/condensate or more than 10^9 m^3 of gas), medium fields (which produced 10^5–10^6 m^3 of oil/condensate or 10^8–10^9 m^3 of gas), small fields (which produced 10^4–10^5 m^3 of oil, $<10^5$ condensate or 10^7–10^8 m^3 of gas) and very small fields (which produced less than 10^4 m^3 of oil or less than 10^7 m^3 of gas). According to the above mentioned classification, the oil and gas fields B and C are medium fields, while the oil and gas field A is classified as a large field.

3. The Dehydration System Technology in the Oil and Gas Fields A, B & C

The dehydration process is performed in separators. These are throughput devices of cylindrical shape (vertical or horizontal). They are used to efficiently separate gas from a liquid phase under a certain pressure and temperature. The retention of the fluids in the processing vessels

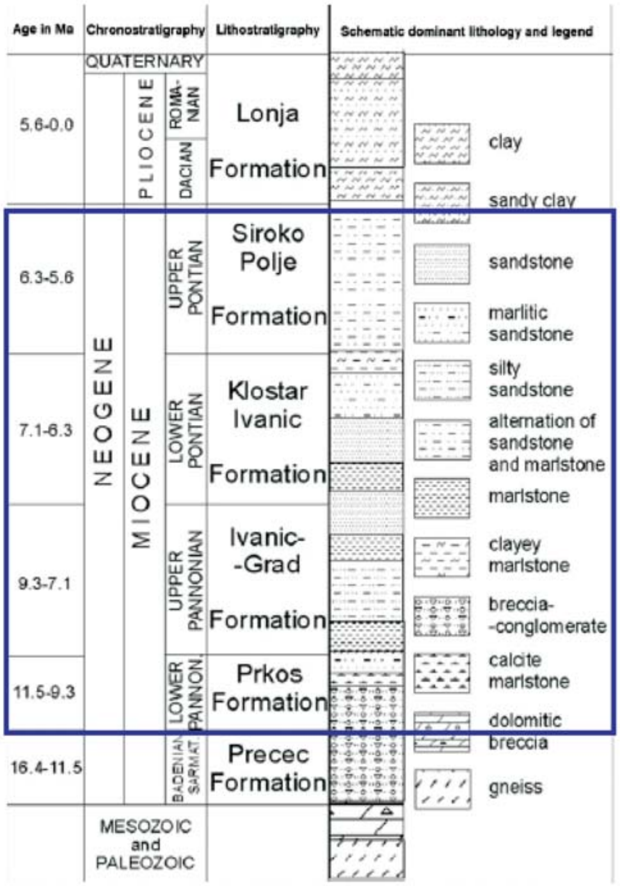

Figure 3: The chronostratigraphy, litostratigraphy and lithology of the Sava Depression (e.g. **Novak Zelenika 2013**)

causes the formation water to be separated at the bottom of the vessel. The amount of the separated formation water regarding the time of its retention is shown in **Figure 5.**

The retention time of the produced water in the treatments vessels is from 3 to 30 minutes (**Arnold & Stewart, 2008**). The technological process of produced water separation in the oil and gas field A is represented in **Figure 6**.

The formation water is processed at three gathering stations, and the dehydration process is done by using formation water separators and dehydrators. The average value of process parameters in field A are: fluid flow: 2 000 m^3/day, pressure: 1.0-1.5 bar and temperature: 35-40 °C. The technological process of produced water separation in the oil and gas fields B and C is represented in **Figure 7**.

The produced fluids are gathered from five measuring stations at the dispatch station of the oil and gas fields B and C. Fields B and C have a common gathering system, and thus a common dehydration system. Due to this, the common dehydrating system for fields B & C may be viewed as a single technological process. The average value of process parameters in fields B & C are: fluid flow: 800 m^3/day, pressure: 1.0-1.5 bar and temperature: 40-45 °C. The formation water separation is performed in the gravity settling vessel and dehydrator.

4. The Formation Water Separation costs in the Oil and Gas Fields A, B & C

The amount of the separated formation water from 2009 to 2015 is shown in **Figure 8**.

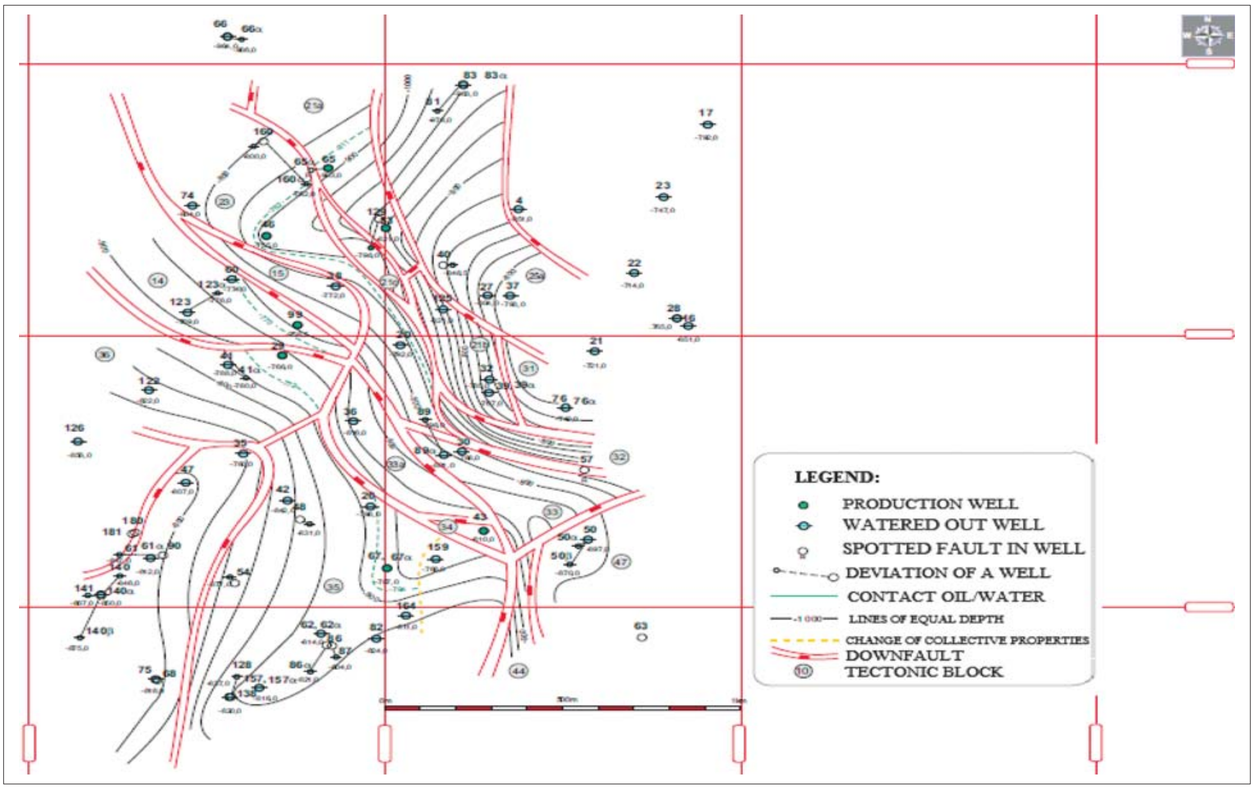

Figure 4: The reservoir structure of field B (from **)

Figure 8 shows an evident increase in the amount of the produced formation water from field A. This is a consequence of the additional optimization of the wells in the analyzed oil and gas field (field A). The optimization of the oil and gas field A was achieved through well workovers. Capital workovers are made on six wells. Capital workover operations in production wells cover operations performed in formations (formation remedial operations), and in the wellbore (equipment repair operations, etc.). The consequence of these capital workovers was an increase of the produced fluids, and the formation water. The oil and gas fields B and C were not optimized. To calculate the overall unit cost, data regarding the energy sources' price (electric energy and natural gas) is needed. These are shown in **Table 1.**

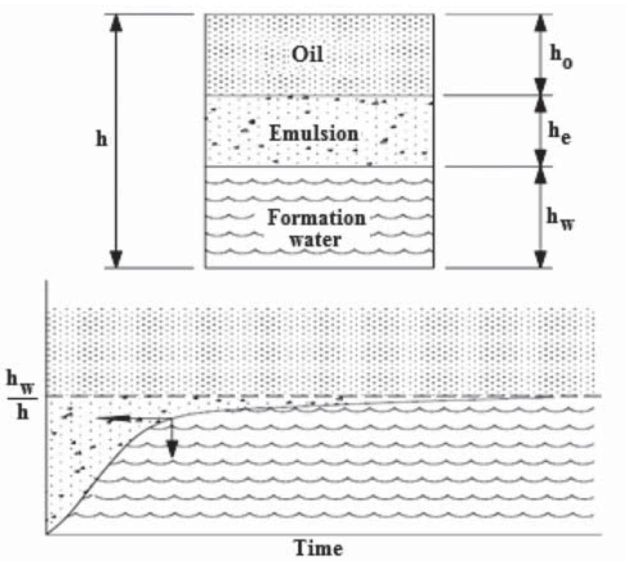

Figure 5: The separation of the formation water as a function of retention time **(Arnold & Stewart 2008)**

The data from **Figure 8** and **Table 1** was used for the calculation of the unit price of formation water separation according to the methodology of the authors **Ivšinović & Dekanić** from 2015. The calculated formation water separation costs regarding the fields A, B and C are shown in **Table 2**.

According to **Table 2,** the costs with the largest share in the overall costs of formation water separation are: energy (field A: 41.0%, fields B&C: 73.3%), heat exchangers and process vessels maintenance (field A: 32.3%, fields B&C: 10.5%) and chemicals (field A: 21.1%, fields B&C: 11.4%). A statistical evaluation of the above-mentioned data will be made and a correlation between the most important variables will be presented in the following chapters.

5. The Chosen Statistical Methods for the Data Processing

The normal (Gauss) distribution is the most well-known and, in nature, the most common distribution function. It is commonly used in geology and hydrocarbon reservoirs geology (e. g., **Malvić & Medunić 2015)**. The Shapiro and Wilko (S-W) test is the most common

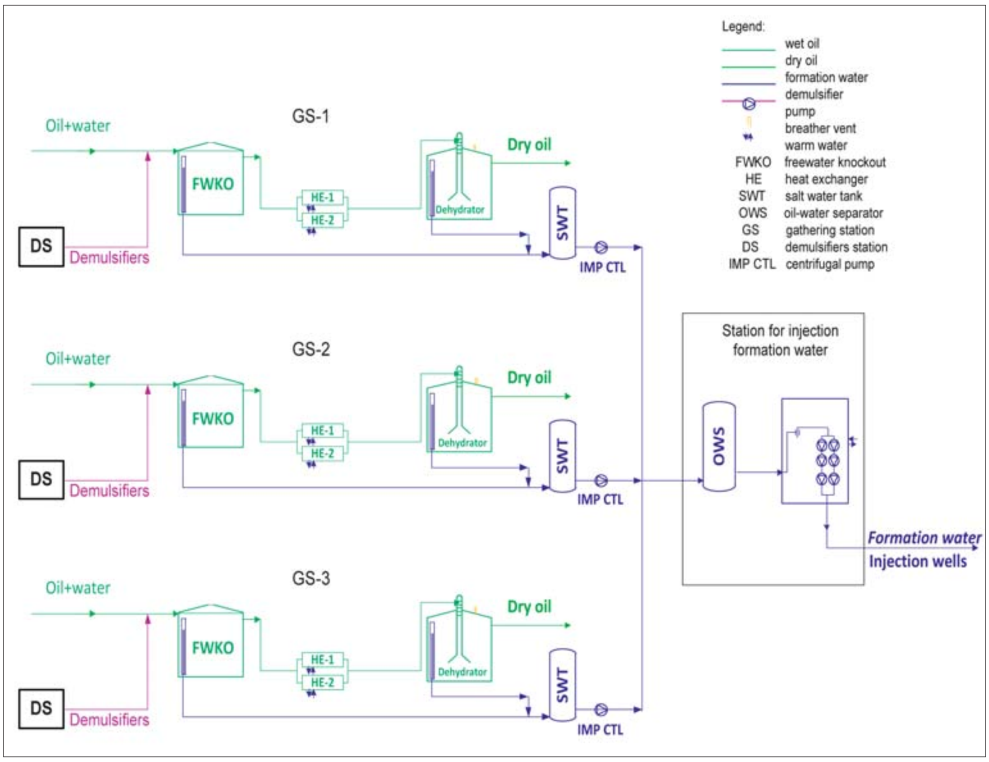

Figure 6: The technological process of formation water separation and collection in the oil and gas field A (**Ivšinović 2016**)

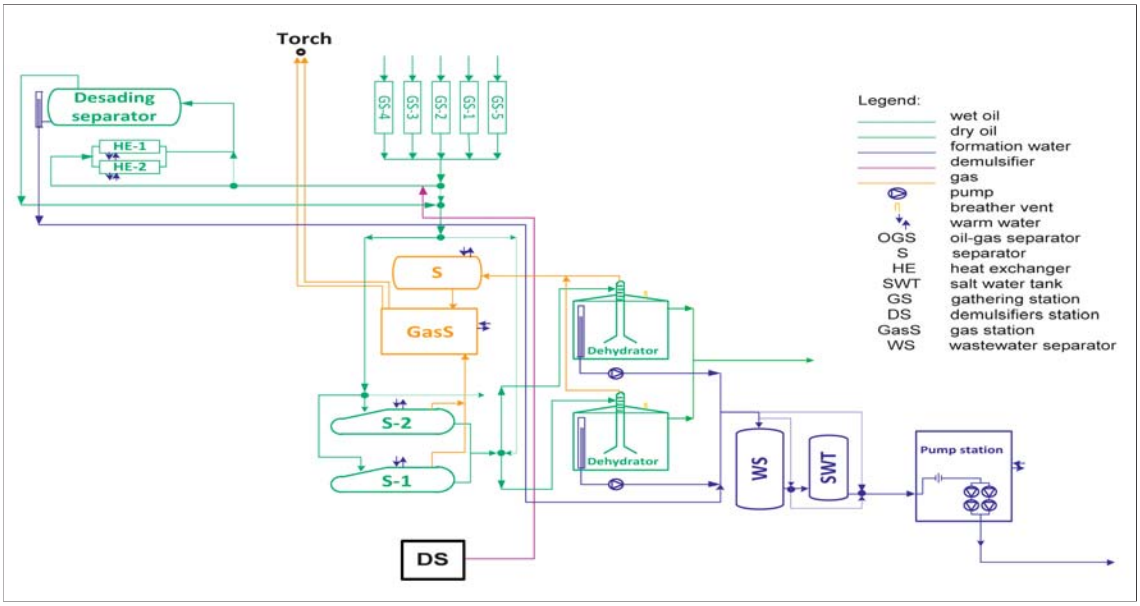

Figure 7: The technological process of formation water separation and collection in the oil and gas fields B and C

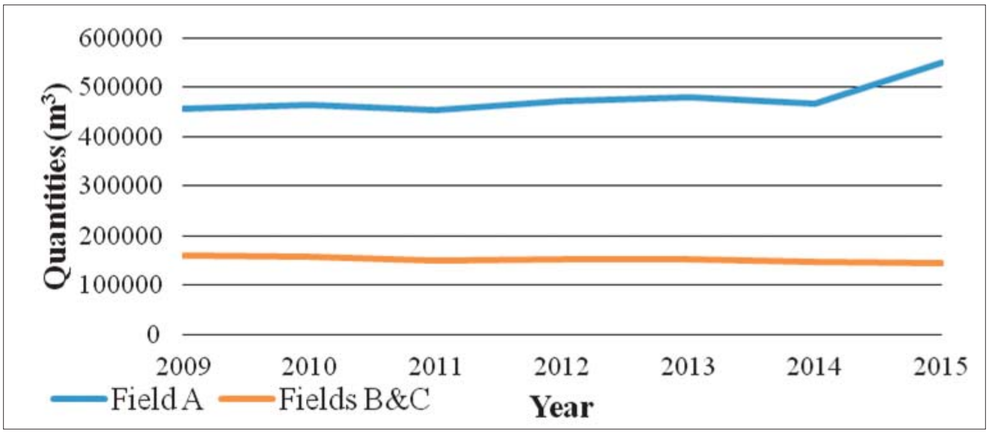

Figure 8: The separated formation water from the oil and gas fields A, B and C regarding the period from 2009 to 2015 (**from** *)

Table 1: The average price of industrial energy sources regarding the period between 2009 and 2015

Year	Electrical power (USD/kWh)	Natural gas (USD/m^3)
2009	0.08	0.36
2010	0.08-0.09	0.53
2011	0.08	0.59
2012	0.08-0.09	0.66
2013	0.09	0.64
2014	0.08-0.09	0.60
2015	0.10	0.56

Sources: Energy in Croatia 2014, Sector analysis IEZ, 2015.

one for testing the normal distribution of data. This test is based on the correlation of a sample of the "statistical order" which has a normal distribution. The null hypothesis is the normality i.e. the uniformity of data. The Shapiro-Wilko test (W) is calculated according to the relation (e.g., **Güner et al. 2009**):

$$W = \frac{\left(\sum_{i=1}^{n} a_i y_i\right)^2}{\sum_{i=1}^{n} (y_i - m_1)^2} \tag{1}$$

Where:

W is the test-value,

y_i is the data,

m_1 stands for the arithmetic mean of data,

a_i is the calculated linear regression value for expected values from standard normal "statistical order".

The Shapiro-Wilko test is a regular tool in the statistical calculation in any statistical computational program so it is important to emphasize that the null hypothesis is not accepted if the p-value is inferior or equal to the threshold of significance (0.05). The sample size for individual costs for Fields A and B & C is seven, for each

Table 2: Unit costs of formation water separation in the process of dehydration on the oil-gas fields A, B and C

Field A	Unit cost (USD/m³)						
Description:	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Boiler room and demulsifiers station maintenance	0.01	0.01	0.01	0.01	0.01	0,00	0.00
Heat exchangers and process vessels maintenance	0.14	0.14	0.14	0.14	0.14	0.11	0.00
Energy	0.23	0.33	0.09	0.10	0.10	0.09	0.08
Chemicals	0.08	0.09	0.06	0.07	0.08	0.09	0.05
Staff costs and amortization	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Total:	**0.48**	**0.59**	**0.31**	**0.33**	**0.34**	**0.30**	**0.14**
Fields B & C	Unit cost (USD/m³)						
Description:	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Boiler room and demulsifiers station maintenance	0.01	0.01	0.01	0.01	0.02	0.03	0.04
Heat exchangers and process vessels maintenance	0.23	0.14	0.06	0.13	0.09	0.04	0.01
Energy	0.97	0.89	0.80	0.63	0.48	0.43	0.60
Chemicals	0.13	0.12	0.08	0.07	0.09	0.16	0.09
Staff costs and amortization	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Total:	**1.37**	**1.19**	**0.97**	**0.86**	**0.70**	**0.68**	**0.76**

Table 3: Testing costs of separating formation water on the constancy of normal distribution

Description:	Field A	Fields B&C
	S-W (p-value)	S-W (p-value)
Boiler room and demulsifiers station maintenance	0.365	0.005
Heat exchangers and process vessels maintenance	0.000	0.890
Energy	0.004	0.645
Chemicals	0.629	0.921
Staff costs and amortization	0.004	0.057
Total cost of the separation of formation water	0.392	0.326
Quantity of produced formation water	0.004	0.896

individual cost in **Table 2**. In order to calculate the interval estimation of expectations and choose the adequate method of correlation, the condition for the calculation is the existence of a normal data distribution. **Table 3** shows the test results of formation water separation testing to the existence of normal distribution.

According to the data in **Table 3**, an interval estimation of expectations with a 0.95 confidence level for t-distribution will be made. The costs with no uniform distribution will be shown with a middle value and the belonging corrected standard deviation.

The interval estimation (IE) is calculated according to the following equation (e.g. **Pfaff 2012**; **Benšić & Šuvak 2013**):

$$< \overline{x} - t\frac{s}{\sqrt{n}}, \overline{x} + t\frac{s}{\sqrt{n}} > \quad (2)$$

Where:

$\overline{x}$ stands for the arithmetic mean,

t- the read value from table for t-distribution,

s- corrected standard deviation,

n- sample size.

The non-integral estimation is used when it does not exist uniform distribution. The non-integral estimation is calculated according to the following formula:

$$NIE = \overline{x} \pm s \quad (3)$$

Where:

NIE stands for non-integral estimation,

$\overline{x}$ – arithmetic mean,

s – corrected standard deviation.

The formation water separation costs are estimated in **Table 4.**

The estimated costs from **Table 4** are used in the cost analysis regarding the separation system and a possible optimization and the separation system rationalization. The heat exchangers and process vessels maintenance costs as well as the energy and chemicals costs will correlate with the quantity for the produced formation water, while the energy and chemicals costs will correlate with the heat exchangers and process vessels maintenance costs. To calculate the correlation coefficient, the Pearson and Spearman correlation coefficients will be used. The condition for the application of the Pearson correlation is that the observed samples are normally (uniformly) distributed. The Pearson correlation coefficient is calculated according to the following equation (e.g. **Malvić & Medunić 2015; Mukaka 2012**):

Table 4: Cost estimates (USD/m^3) for the separation of the formation water in oil and gas fields A, B and C

Description:	Field A		Fields B&C	
	IE	NIE	IE	NIE
Boiler room and demulsifiers station maintenance	<0.00 ; 0.01>	-	-	0.02±0.01
Heat exchangers and process vessels maintenance	-	0.12±0.05	<0.03 ; 0.17>	-
Energy	-	0.08±0.02	<0.50 ; 0.88>	-
Chemicals	<0.06 ; 0.09>	-	<0.08 ; 0.14>	-
Staff costs and amortization	-	0.01±0.04	<0.02 ; 0.03>	-
Total cost of the separation of formation water	<0.23 ; 0.49>	-	<0.69 ; 1.18>	-

Table 5: The correlation between the costs of separated formation water for fields A, B and C

Correlation (X vs. Y)	Field A		Fields B&C	
	r_p	r_s	r_p	r_s
Boiler room and demulsifiers station maintenance vs. Quantity of produced formation water	-	-0.679	-	-0.571
Heat exchangers and process vessels maintenance vs. Quantity of produced formation water	-	-0.821	0.962	-
Energy vs. Quantity of produced formation water	-	-0.429	0.767	-
Chemicals vs. Quantity of produced formation water	-	-0.286	0.077	-
Chemicals vs. Heat exchangers and process vessels maintenance	-	0.536	0.141	
Energy vs. Heat exchangers and process vessels maintenance	-	-0.071	0.703	-

$$r_p = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{l}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{4}$$

Where:

r_p stands for Pearson correlation coefficient,

x_i, y_i – sample values x and y,

$\overline{x}$, $\overline{y}$ – mean value of the samples x and y,

n – sample size.

The Spearman coefficient is used when there is no clear linear relation between the two variables if their original values are compared, but if the values are ranked, the dependence can be calculated. It is used in the correlation between the two independent variables. It had earlier been used in the hydrocarbon reservoir calculation in CPBS (e.g., **Malvić 2006; Malvić & Prskalo 2008**). Due to the fact that the coefficient calculation technique is somewhat not affected by the extreme values and the gathering of data in certain regular intervals is not exclusively necessary, it can be applied to little sample "clusters" (e.g., **Mukaka 2012; Gauthier 2001; Malvić & Medunić 2015).** The equation is as follows:

$$r_s = 1 - \frac{6 \cdot \sum_{i=1}^{l} d_i^2}{n \cdot (n^2 - 1)} \tag{5}$$

Where:

r_s stands for the Spearman correlation coefficient,

d_i – the difference between the rankings for each x_i and y_i pair of data,

n – sample size.

According to the results of the existence of normal distribution from **Table 3**, the correlation coefficients among the formation water separation costs for fields A, B and C variables have been calculated (see **Table 5**).

The positive correlation between variables showed a linear increase of both variables. Negative correlation between variables shows a linear increase of one variable, while the second variable records a linear decline. There is a correlation field A (-0.821); fields B and C (0.962) between the heat exchangers and process vessels maintenance and the quantity of produced formation water. There is a middle correlation between the remaining variables pairs which comes as a consequence of the unevenness of the investment during the observed period due to the decrease of operational costs caused by the decrease in the price of crude oil on the markets. The non-correlation among the chemicals and energy and the heat exchangers and process vessels maintenance is the consequence of the decrease in the investments in the formation water separation system.

7. Conclusion

The formation water separation costs in the oil-gas field A range from 0.14 USD/ m^3 to 0.59 USD/ m^3. The average year amount of produced formation water is 478 000 m^3. The formation water separation costs in the oil and gas fields B and C range from 0.68 USD/m^3 to 1.37 USD/m^3 while the average year amount of produced formation water is 152 000 m^3. The difference in the unit cost is caused by the difference in the amount of produced formation water, energy sources, the physical and chemical content of the fluids and the process maintenance. There is a correlation between the heat exchangers and process vessels maintenance and the quantity of produced formation water. There is a middle correlation between the energy and the quantity of produced formation water, and no correlation between the chemicals and the quantity of produced formation water, etc. The consequence of the lack of investment into the separation system is the zero correlation between chemicals and heat exchangers and process vessels maintenance. The lack of uniformity regarding the data is a consequence of the reduction of formation water separation costs. This however is the consequence of the lower price of crude oil on the world market. The formation water separation costs regarding mature oil and gas fields represent a significant share in the overall costs which can, in a certain moment and with a certain combination of technological factors and energy prices, be fundamental for the cost calculation and a business decision regarding the possible continuation of hydrocarbon exploitation in such fields.

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SAŽETAK

Analiza troškova izdvajanja slojne vode iz ležišta ugljikovodika na primjeru gornjomiocenskih ležišta u pješčenjacima Savske depresije

Slojna voda crpi se tijekom radnoga vijeka ležišta ugljikovodika zajedno s naftom i/ili plinom, uglavnom predstavljajući dominantan fluid iscrpka. Proizvedena slojna voda odvaja se u procesu dehidracije. U ovome radu obrađeni su troškovi odvajanja slojne vode na naftno-plinskim poljima A, B i C koja se nalaze u zapadnome dijelu Savske depresije. Na polju A proces odvajanja slojne vode odvija se na trima lokacijama, dok se na poljima B i C proces obavlja na jednoj lokaciji. Prikazan je tehnološki sustav odvajanja slojne vode te geološke karakteristike ležišta na spomenutim poljima. Napravljena je statistička obrada troškova odvajanja slojne vode. Procijenjeni su troškovi te je napravljena korelacija između troškova važnih za odvijanje normalnoga procesa odvajanja slojne vode. Svrha analize troškova procesa dehidracije jest optimizacija proizvodnoga sustava te kontrola troškova procesa.

Ključne riječi
ekonomika slojne vode, statistička procjena, korelacija troškova, Savska depresija

Author contribution:

The author has prepared the whole work.